Design of a Lunar Excavator

ME 4182

Dr. Brazell

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Group Tu-5:30

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Outline

Abstract

When NASA begins lunar construction, various types of site clearance equipment will be required. We assume lunar construction requirements will dictate the use of a type of equipment to dig trenches and foundations, the lunar equivalent of a backhoe. This paper describes the results of a project by a group of five M.E. students to design a lunar backhoe.

Problem Statement

Background

NASA has recently started some preliminary design studies for a lunar base. The proposed lunar base has created a need for several types of site clearance equipment to be designed for the lunar environment. We decided to design the equivalent of an earthmoving backhoe. Dragline and blower type pieces of equipment were considered as alternatives but discarded in favor of the more traditional backhoe type.

It was decided a lunar backhoe with capabilities similar to a tractor mounted earth backhoe would be the most versatile and also sufficient for most demands. The design will be constrained by the cargo capacity of the present space shuttle system. Other constraints will be imposed by the lunar environment, such as extremes of temperature and low pressure. The design will also have to take into account the lower lunar gravity and the characteristics of the lunar regolith.

Performance Objectives

Digging Depth	10 feet
Digging radius from swing pivot	12 feet
Loading height	10 feet
Loading reach	10 feet
Swing arc	155^{o}
Digging force	10,000 lb_f
Design life	1 Earth year

Constraints

Environmental temperature	-100 to 130°C
Hydraulic supply pressure	2250 psi
Hydraulic supply flow	25 gpm
Size	60 x 15 feet
Weight	65000 lb_f on Earth
Radiation	Resistant

Detailed Description

Materials

Materials selection for this project was critical. The most important factor involved is the temperature range of -100 to 130 °C in which the materials had to operate. The upper limit is of little practical importance since most materials have good mechanical properties at that range, but the lower limit is a limiting factor. Metals and polymers tend to be ductile at high temperatures and brittle at low temperatures, and the temperature at which the material changes from mostly ductile to mostly brittle behavior is the transition temperature (TT). Materials with high TT's become very brittle at low temperatures, and will propagate cracks to the extent that failure will occur below the ultimate tensile stress. This becomes very important because low temperature brittle behavior will cause failure during shock loading and our equipment is likely to experience a great deal of shock. Except for the lowering of the TT, other mechanical properties are improved at low temperatures, such as ultimate tensile strength, yield strength, and hardness. Static and light loads are not problems at low temperatures.

Irradiation is another consideration in the material selection, and the single significant effect of irradiation is a decrease in the TT. Most studies of irradiated metals involve those used for nuclear reactors where the radiation is magnitudes greater than on the lunar surface. For a design life of less than two or three years, the irradiation effect will be negligible, with only a slight increase in brittle behavior. Should the design life be lengthened, a coating would be necessary to protect the metal. Such coatings are typically lead-base or, oddly enough, uranium. Our short design life requires no special treatments.

The final major consideration is the strength-to-weight ratio. Our materials should be lightweight, since transportation to the moon is likely to be an important factor, and they should be strong enough to operate safely and not produce a bulky design. For these reasons, a material with high strength-to-weight ratios is necessary.

Several types of materials were examined. In metals, fcc structures are by far the best for low temperatures, since the high number of slip systems allow ductile behavior. Steels are hard and strong, but have TT's of about -60°C and become quite brittle. There are two austentitic, low-carbon steels, one with .05%C, 3.5%Ni and another with .05%C, 8.5%Ni which are suitable for low temperature loading. They are quite strong and hard and have mechanical properties very close to those of other steels. Other alloying elements which help low-temperature properties are manganese (up to 1.5%)and silicon (up to 0.6%), but sulphur, copper and phosphorous should be kept to a minimum. The 8.5%Ni steel is somewhat stronger at higher temperatures than the 3.5%Ni steel.

Aluminum alloys seemed to be very good due to their high strength-to-weight ratios and fcc structure, and most alloys are ductile, shock-resistant, and display no blatant change from ductile to brittle behavior. Magnesium is the most beneficial alloying element, and Al-Mg alloys perform well at temperatures as low as -162°C. The 2000 and 7000 series are mostly used in aircraft applications; the 2000 series have good properties up to about 180°C after which their strengths reduce gradually, and the 7000 series acts similarly up to about 150°C. Both have high strengths, moderate hardness and good ductility, with the 7000 series being somewhat stronger. The recent Al-Li alloys are emerging as excellent alloys for strength at low temperatures, but they are not fully tested and tend to show poor fracture toughness and exhorbitant prices.

Several other materials were also considered. Cast irons were far too brittle to be used. Titanium alloys have high strength-to-weight ratios, but their hcp structure caused a fairly high TT. Magnesium alloys are often used for satellites, but they proved useful for only static and light loading due to the hcp structure. Graphite reinforced composites are emerging as high strength, lightweight materials for use in fighter airplanes, but there is very little test data available and they are extremely high priced.

The backhoe design uses three different materials for its structure. The large body members are to be cast from Al-7075. This alloy was chosen for its good low-temperature ductility, high strength-to-weight ratio, and good castability. A cast design is to be used as opposed to welds, and it will be fastened with bolts and rivets. Welding will allow cracks to propagate and fracture the material under brittle conditions, thus it was found that 20% of the hulls of "all-welded" ships early in WWII cracked completely across in cold northern waters. Bolt holes will be located away from highly stressed regions. Smaller members which will not experience heavy shocks will be cast or drawn from Al-2024. This is the material used for most of the lunar rover, and it is strong and light. The third material is a steel containing 0.05%C, 3.5%Ni, 0.3%Si, 1.2%Mn and other trace elements; it is double normalized at 1650°F and 1450°F, followed by reheating to

1050°C, and air cooling. It is to be used for the pins, bucket teeth, and the interface with the prime mover. It was chosen because the steel is much harder than aluminum alloys, and it performs much better at the high temperatures which might be experienced by these parts. A decision matrix for materials selection is located in the Appendix.

Lubrication

Lubrication will be very important to the design. An organic solid film lubricant is needed for a space environment, and the main criterion is the friction coefficient which should be less than that of a 0.001 inch thick film of gold. The following are the requirements of the lubricant:

(1) Resist degradation from air and water vapor during preparation for launch.

(2) Withstand loads, acceleration and vibrations during launch.

(3) Be nearly unaffected by the temperature ranges during launch and in use.

(4) Be stable at very low pressure.

(5) Have low friction coefficient.

(6) Have long wear life.

(7) Resist radiation.

The lubricant must be applied to a clean surface. It is first filtered, then mixed with a binder and fluid dispersant (usually water). It is applied with a dry nitrogen air brush, then air dried in an air-circulating oven.

Selection of the binder is also critical; it must meet the following:

(1) Insoluble and non-reactive in water.

(2) Melting temperature greater than $560^{\circ}F$.

(3) Resist oxidation at temperatures below $400^{\circ}F$.

(4) Low vapor pressure at $400^{\circ}F$.

(5) Must cure at temperatures low enough not to affect heat treating properties of the metals.

Fortunately, NASA conducted experiments over a vast number of lubricants and binders. Using their information, a selection can be made which will suit our particular requirements:

	Lubricant	Binder
Light Loads:	MoS_2 and graphite	bismuth and sodium silicate
Heavy Loads:	MoS_2 and gold and bismuth	graphite and sodium silicate

These lubricants and binders were the result of intensive research by NASA in 1963. Although the information is over twenty years old, the lubricant and binder are more than sufficient for our purposes, especially since our design life is approximately one year. An added advantage of these lubricants is that there is no maintenance which needs to be performed after application.

Ergonomics for the Controls

The controls for the backhoe were arranged so that they could be operated by an astronaut wearing the current shuttle spacesuit. Since any changes in space suit design will probably be to increase their mobility or utility, this control arrangement should be acceptable to most present and future astronauts. The design is also in agreement with SAE standards for the type and arrangement of controls for backhoe operation. All control movements are the same as these on regular backhoes and are labeled with simple pictographs.

The spacesuit allows approximately 85% of nude range mobility; however, this is an average and while some movements are almost normal, some are severely restrained. The vision of the astronaut is confined to a 120° arc from side to side in the horizontal plane. Placing the operator directly behind the backhoe arm in a fixed seat would have meant that whenever the arm was swiveled to one side it would have been beyond the operator's range of vision. This problem was resolved by placing the operator along side the boom so that he rotates with it. All of the control levers have been positioned so that they will be within the optimum area for one or two handed operation for a crewman seated at the control station. The spacesuit will allow the astronaut to lean side to side from the vertical by 30°. The control arrangement allows the two main controlers to be operated even in this extreme position.

The seat design is derived from that used on the lunar rover which was nylon webbing on an aluminum frame. This arrangement is both lightweight and provides a degree of vibration isolation. In this case, the webbing will be made out of a Kevlar based fabric which is quite a bit stronger than nylon. The seat has been proportioned for a man wearing the current portable life support system (PLSS) which will rest directly against the back of the seat. No armrests have been placed on the seat so as to allow the crewmember as much lateral movement possible. A grab bar runs along the top of the control panel to help the astronaut to get into and out of the seat. This was necessary because the astronaut is sitting with his waist at an angle of 90° which is about as far forward as he can bend. While this provides a maximum amount of forward vision over the control panel, it also makes it quite difficult to get out of the seat unless there is something for the operator to pull himself up with. A seat belt is provided to ensure that the operator will remain in the seat.

The control station itself is made from Al-2024 and access to control valves is allowed by removing a panel at the rear of the control station. All hydraulic lines run from the control valve out the bottom of the control station.

Bulldozer-Backhoe Interface

The interface between the bulldozer and the backhoe is a major structural component of the backhoe. Due to the large loads encountered it is made predominantly of the 3.5%Ni steel specified, although a few components are made of Al-2024. Fasteners consist mainly of rivets in the interest of low maintenance. Welding and bolting were investigated as fasteners but were discounted; welding due to embrittlement at low temperatures and bolting due to high maintenance requirements.

The backhoe is attached to the bulldozer by a four point hitch. Fairly common on Earth construction equipment, it provides a stable mount with ease of attachment. It can easily be scaled up or down to fit various size requirements of the bulldozer or the backhoe.

The boom is attached at a pivot point where it is free to swing through an arc of approximately 160°. It is a bottom mounted boom where the boom is mounted below the boom cylinder; this best serves the purpose of protecting the boom cylinder from any flying debris.

The control cell, consisting of the operator's chair and control panel, is mounted to one side of the boom in such a way that as the boom pivots, it also rotates the operator's chair. Thus the operator will always have a relatively unobstructed, straight ahead view of the area he is digging; this is important due to his reduced field of vision through the astronaut helmet. Since the control cell is mounted to one side of the boom, it limits the angle of swing on that side. The design allows a 90° swing away from the control chair and a 60° swing toward the control chair.

The boom swing is controlled by two hydraulic cylinders mounted to the main frame plate. A rack and pinion controlled swing was investigated, but a two cylinder arrangement is easier to maintain and mount. A hydraulic manifold will be mounted near the main pivot point to allow easy maintenance and orderly routing of hydraulic lines. Mounting points were provided for stabilizer arms. It was decided that Earth style stabilizer arms manufactured with standard steel would be adequate since there will be little if any shock to the stabilizers. If the construction needs dictated backhoe use in an unstable soil environment, longer arms and larger feet could be retro-fitted with very little trouble.

Hazard Analysis

Failure

There are three categories into which failure occurs, failure of members, failure of hydraulic cylinders and failure of hoses. There are two ways a member can fail, it can yield or it can fracture. At the low temperature conditions, any failure that would occur would be brittle fracture. Since the materials were chosen very carefully, there is very little chance of this happening. At the high temperature conditions, failure will generally be due to yielding, and if the load increases, fracture. This is somewhat more likely since the temperatures near the pins might get higher than ambient, where the yield strength of Al-7075 begins to decline. To protect against this, our design incorporated built-up areas near the pins. Since stress equals load divided by area, a larger area reduces stress. Our design should have been more than adequate to avoid yield. The consequences of fracture are rather sever; there will be no practical way to repair it, and there will be no replacement. It is not so bad if a member yields. First, the operator will see the strain if he attempts to overload, and most likely reduce the load. Most of the strain he can see will be elastic strain with no permanent effects on the member. Should there be some permanent deformation, it will probably not affect the backhoe drastically; it will still work.

The hydraulic cylinders can also fail, and they are somewhat complicated internally. If there is a problem inside a cylinder, an operator could probably fix it with a few hours inside an airlock, but not necessarily. It is much more practical to bring extra cylinders as replacements. This eliminates operator repair to loosening and tightening two bolts. It is rather unlikely for the cylinders to fail internally, but a much more common failure is the failure of an outer O-ring. In this event, the operator will replace the O-ring, requiring removal of the cylinder. The repair can be done in a few minutes inside the airlock, and is very simple requiring no tools.

The hoses and couplings can also fail, although it is very unlikely. Should a hose fail, it would probably be a small leak and could be repaired inside an airlock, or possibly even outside. Should the hose fail and be non-repairable it will need to be replaced. It will involve somewhat complicated work outside, but it can be done. If either a hose or cylinder fail, it will only leave part of the backhoe non-functional. It is likely that a great deal of the project will be finished by then, and a partially functional backhoe might be adequate to finish the project.

Use and Misuse

The backhoe is designed to dig holes and trenches on the lunar surface. It is attached to the back of a prime mover, and anytime the backhoe needs to move to another position, the prime mover must be moved. The backhoe can also be used to lift and move other objects like a large arm.

There are several ways in which an operator can cause problems by not being careful. The first problem which he might encounter is moving the backhoe from the transporter to the prime mover, and attaching it. Most likely, he will only move it a short distance, and since the procedures for attachment are very simple, there should not be any major problems.

The backhoe is supplied with a seat belt, which should be worn when the operator is on the backhoe. If the operator does not use it, there is a possibility of falling off the backhoe. In many circumstances, even this will not be a problem, but if the prime mover is being moved at the time, the operator might be run over. It is also possible for him to fall onto the backhoe mechanism or in the hole being dug; either case could damage his spacesuit or hurt him.

If the operator applies a high force to the backhoe at very high temperatures, there is a possibility that heated portions near the pins will begin the yielding process. The initial deformation is temporary elastic strain, but a higher force will cause permanent deformation. These high forces are most likely to occur during digging rather than lifting due to the low gravity force. If the operator notices the yield, he should remove the force and use another approach, but if he does not notice or continues to force the member, plastic deformation might occur. If the force is raised even higher and continued, there is a chance of fracture. Both these circumstances are very unlikely, since the operator will be in a position to constantly see the members.

Another problem for the operator is due to the intensity of the sun. If he catches a strong reflection off a mirror or shiny surface, it is possible for him to harm his eyes. Hopefully he will be aware of this possibility, take care not to casually look around, and be aware of reflective surfaces.

Due to the looseness of the lunar soil, it will not support itself around holes like Earth soil. With the range of motion of the backhoe, it is possible to undermine the backhoe itself, and have it fall into the hole. The operator should be aware of this, and take care not to dig out the soil that supports him.

It is also possible due to carelessness or lack of peripheral vision, to hit something when the backhoe rotates. This will not cause failure of the backhoe, but it could either jolt the operator or hit another astronaut. Since the backhoe is designed to move slowly, this can happen only with extreme carelessness. Nobody need be near the backhoe while it is operating and there will probably not be a great deal of equipment near the hole.

Since the momentum of objects is the same and the frictional force of objects on the surface is one sixth on the moon as on Earth, sideways swings could rotate the whole prime mover in its attempt to stop it. This would only be a problem on slopes, and since the backhoe rotates slowly, this will generally not happen. However, the operator should be aware of the possibility.

The final possibility of misuse deals with the use of the backhoe. Should it be used improperly, the vehicle could be lifted from the surface or tipped over. It is important for the operator to become familiar with the equipment on Earth under safe conditions before he needs to use it on the moon.

Maintenance, Operation, and Tests

Maintenance

The only regular maintenance required for our design involves the hydraulic system. The simplest way to assess the condition is to regularly check the fluid level; if it is low, there is probably a leak in a hose or valve and it must be investigated. For extended usage, there would be other maintenance to perform on both the backhoe and the prime mover. Lines should be cleaned periodically and the system should be checked for pressure. On the prime mover, the fluid would need to be drained and changed, and the fluid filter cleaned or replaced. This maintenance will not be necessary, however, over the short-term, and generally involves the hydraulic system of the prime mover rather than the backhoe itself. The lubrication process need only be performed once, before the launch. Should there be a problem, the operator will have some spray lubricant which can be used in the space environment.

Spare Parts

Most parts that are subject to failure should be included as spare parts, with the exception of the major structural members. The most important part of the backhoe besides the structural members is the control valve. The valve is not expected to fail during use, and since it is very heavy, it might be desirable not to bring a spare. The problem is that if it fails unexpectedly, the backhoe will not operate. Our recommendation is that if there is room for an extra, it should be taken. There should definitely be an extra spring-binding and some extra O-rings since these are the most common failures.

Other major components are the hydraulic cylinders. There should be at least one spare cylinder for each size; this avoids the problem of trying to repair a cylinder. If however, two cylinders of the same size fail, it would be wise to have spare V-packings, wear rings, and snap rings for each size in order to deal with an emergency. There should be several O-rings taken as spare since these often fail, and they are simple to replace. Also the equipment needed to replace these parts must be included.

There is a variety of other parts that should also be taken. Pins of each size should be included since a yield of pins due to high forces is a slight possibility. Extra hydraulic hose and couplings should be available in case the hose fails during use. It will be necessary to have rudimentary tools to perform the replacement operations, and a spray can of solid lubricant should be included (care must be taken to insure that it is not under high pressure). Extra hydraulic fluid, filters and a hydraulic pump will also be necessary to maintain the prime mover in operable condition.

Backhoe Operating Instructions

(1) When the operator is seated, he should secure himself with the seatbelt.

(2) The two short levers on either side of the control panel control the stabilizers. Pushing forward raises the stabilizers. Pulling back lowers the stabilizers.

(3) The two central levers control the motion of the boom, dipperstick, and bucket. For the left lever:

Pushing forward raises the dipperstick.
Pulling back lowers the dipperstick.
Moving right rotates the boom to the right.
Moving left rotates the boom to the left.

For the right lever:

Pushing forward lowers the boom.
Pulling back raises the boom.
Moving right empties the bucket.
Moving left causes the bucket to scoop up soil.

Attaching Backhoe to Bulldozer

(1) Attach the pressure and return hoses.

(2) Raise the backhoe mainframe with the hydraulic system by extending the stabilizers.

(3) Back the bulldozer to align the attaching points with the backhoe mainframe.

(4) Secure each side of the mainframe to the bulldozer.

Separating Backhoe from Bulldozer

(1) Lower the stabilizers until they are supporting the weight of the backhoe. Retract the bucket and dipperstick and extend the boom cylinder until the backhoe is fully extended and resting on the gound.

(2) Detach the backhoe mainframe from the bulldozer.

(3) Retract the stabilizers until the mainframe is resting on the ground tilted slightly forward.

(4) Relieve pressure in the hydraulic system by shutting off the hydraulic pressure to the backhoe and operating all of the control valves.

(5) Disconnect the pressure and return hoses.

Hydraulic Circuit Tests

Test the valves for leaks as follows:

(1) Raise the loaded bucket a few feet off the ground and shut off the hydraulic pressure to the backhoe.

(2) Disconnect the dumpline from the control valve.

(3) If the load settles and oil is leaking past the control valve, oil will leak from the disconnected oil line.

(4) Reconnect the line and lower the bucket to the ground.

Performance Test

A close estimate of the backhoe performance could be obtained on Earth by replacing the backhoe's current bucket with one of a smaller volume, and conduct testing on loose, rocky soil similar to lunar regolith. The change in conditions will not alter the digging force, but it will alter the lifting force. A bucket of the proper size would approximate these conditions fairly well. The purpose of the performance testing is not only to test the ability of the backhoe to function, but also to help the operator become familiar with it under safe conditions.

Conclusions

Conclusions and Recommendations

The design of this backhoe is very similar to conventional earthmoving equipment, however significant changes had to be made to adapt to the lunar environment. The major environmental considerations were the temperature extremes and low pressure; radiation did not present major problems for the short term. Since the backhoe will have to be transported by the space shuttle and then ferried to the moon, materials with a high strength-to-weight ratio were also required. The final design uses a combination of Al-2024, Al-7075, and 3.5%Ni steel. The lubricant had to survive under the same environmental conditions, and two MoS_2 based lubricants with two different binders were selected.

It was important to use a design which could be easily maintained and repaired in a lunar environment. This design also had to be usable by someone wearing a spacesuit. The control cell had to be placed so that the operator rotated with the boom to allow greater visibility. The controls had to be arranged so that they would be convenient for a person in a spacesuit who is similar to a severely handicapped person. The actual operation of the backhoe is a straightforward process almost exactly like conventional backhoes, and the control layout follows SAE standards. The bulldozer-backhoe interface consists of a conventional four-point hitch.

There are certain topics which we would have investigated further if we would have had the time. One aspect which can be improved upon is the fold-up characteristics of the backhoe assembly. Since there is a limited amount of room on shuttles, it is important to make the best use of the room provided. Our design will fit inside the compartment, but not in as efficient a manner as possible.

Another aspect of improvement has to do with the maintenance of the backhoe. The suggestions for further development are using hydraulic cylinders of the same size for as many parts as possible and designing quick-release mechanisms for all parts which might need to be removed for repair or maintanance. This would allow for fewer spare parts and simpler repair. The pins could also be made to be the same size.

Although our design is probably very adequate, it might be possible to improve upon it by extensively designing each member of the backhoe to a greater extent, our group was constrained by time. Also, the use of graphite reinforced composites should be investigated to a greater depth. Since they are on the leading of present technology, it might involve extensive research of very recent periodicals and reports. This information is subject to be very difficult to obtain and work with. Aluminum-Lithium alloys might also be investigated.

The surface preparations for our design were deemed to be unnecessary, but there might be other factors which we did not consider. Radiation might not be a problem, but the different environment might produce a situation in which a surface preparation might be desired. Of concern is the aluminum and steel interfaces, and they might need some sort of protective coating in order to perform properly during use.

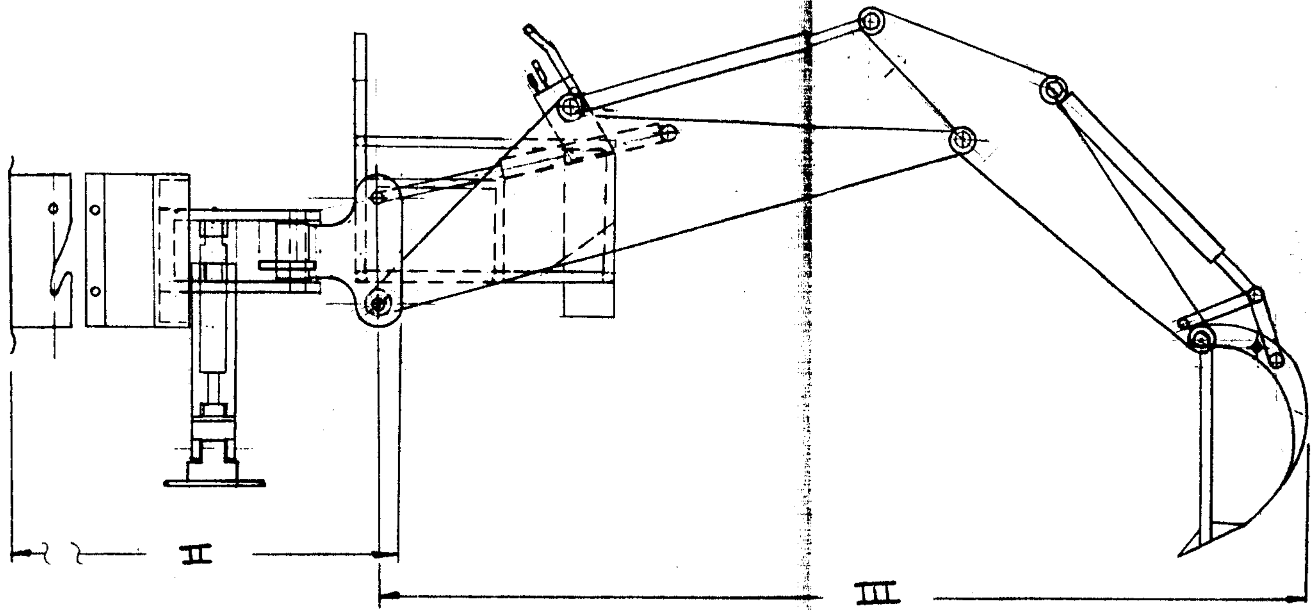
Other work can still be done to investigate the effects of the lunar environment on the hoses and hydraulic fluid. Our design called for the use of a non-water base hydraulic fluid and metallic hoses. Our project did not include a detailed cost analysis, and if such an analysis is required, it would also be the topic for more work. It is likely that the next lunar mission might not have the unlimited budget that the first lunar missions essentially enjoyed, and the mission might even have to be economically profitable using income from experiments or mining.

Our project laid the basic groundwork for a more detailed project which has a longer time span in which to work with. Although we feel this design is very competent, it is by no means ready to be manufactured and put into use. Our report explains the areas in which we concentrated our efforts, and the conclusion explains where future efforts might be directed.

Detailed Drawings

II. INTERFACE ASSEMBLY

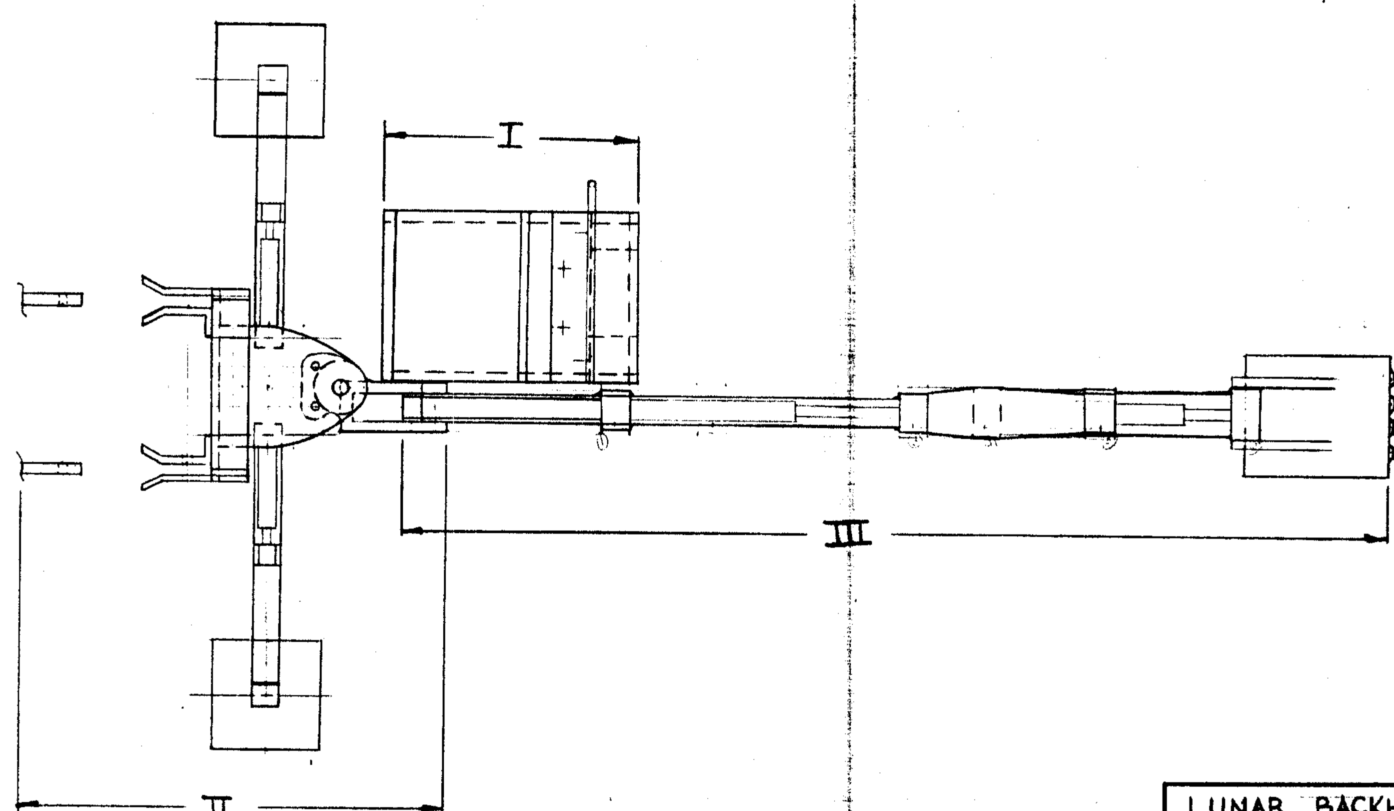
III. ARM ASSEMBLY



LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1:20 / DATE: 12 MAR. 85	APPROVED BY: C. GAMBINO	DRAWN BY / REVISED
ASSEMBLY DRAWING, SIDE VIEW		
ME 4182 TU-5:30		DRAWING NUMBER 1 OF 22

11 X 17 PRINTED ON NO. 1000H CLEARPRINT

I. OPERATING ASSEMBLY
II. INTERFACE ASSEMBLY
III. ARM ASSEMBLY



LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1:20 / DATE: 12 MAR 85	APPROVED BY: C. GAMBINO	DRAWN BY: Gambino / REVISED
ASSEMBLY DRAWING , TOP VIEW		
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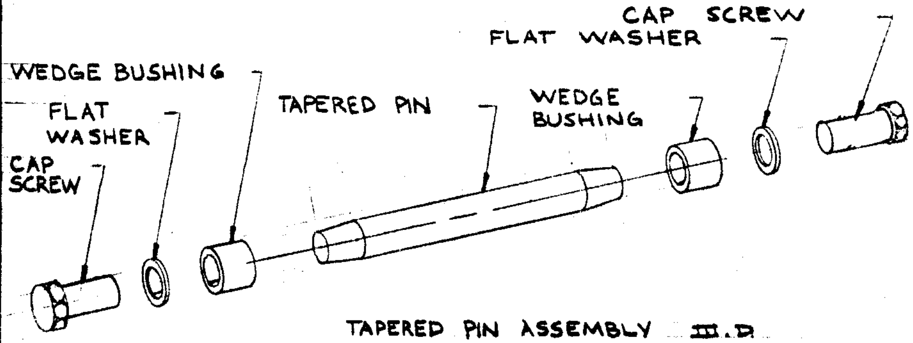
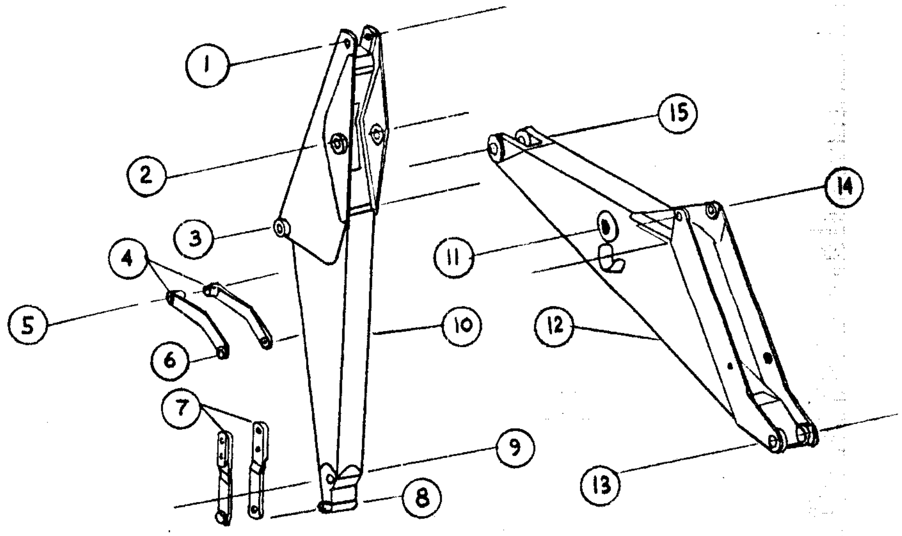
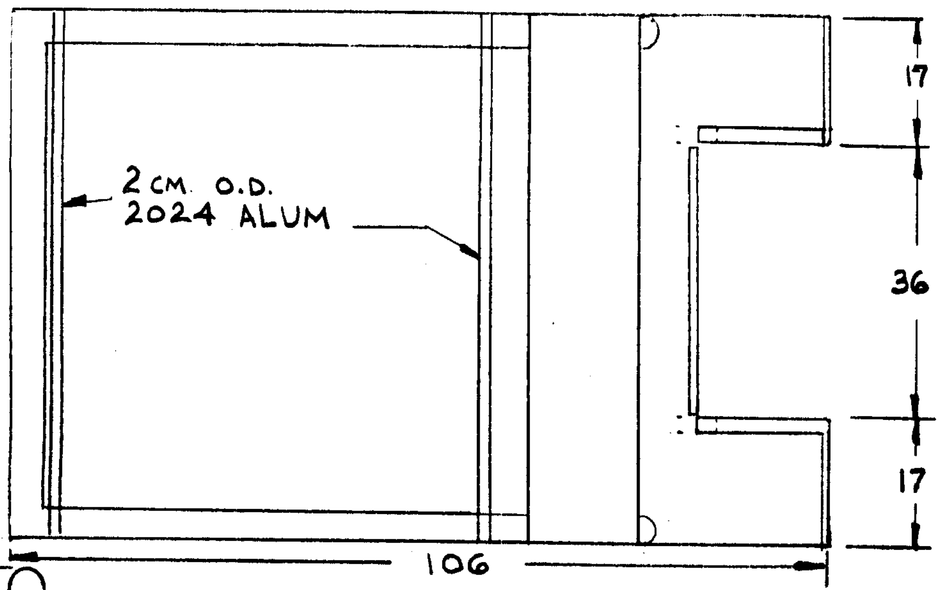


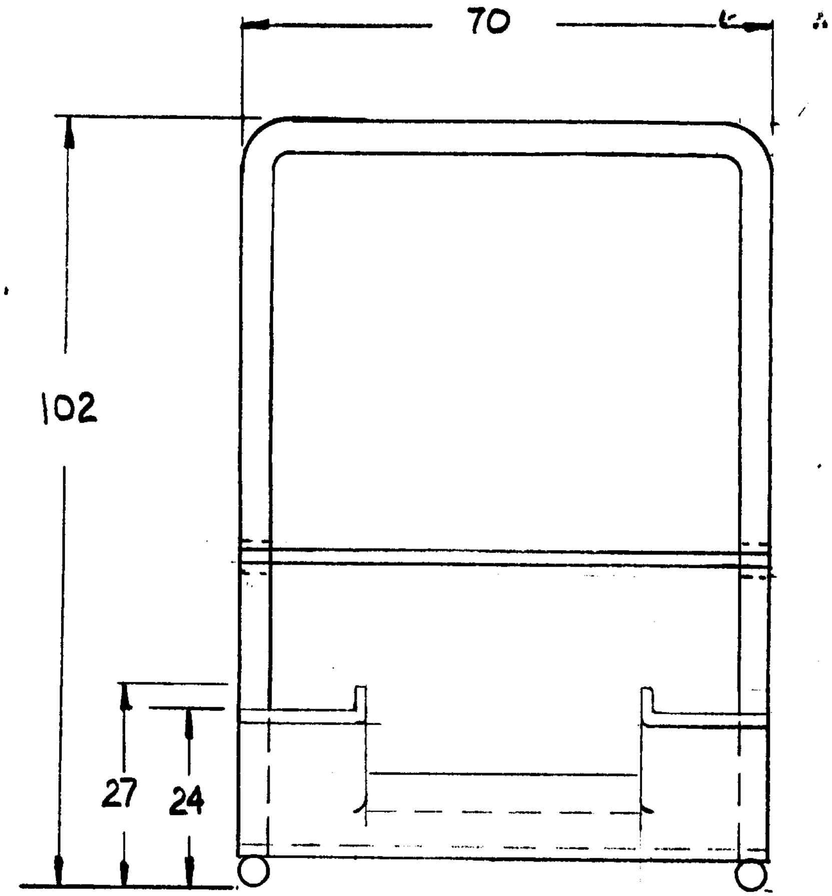
TAPERED PIN ASSEMBLY III.D

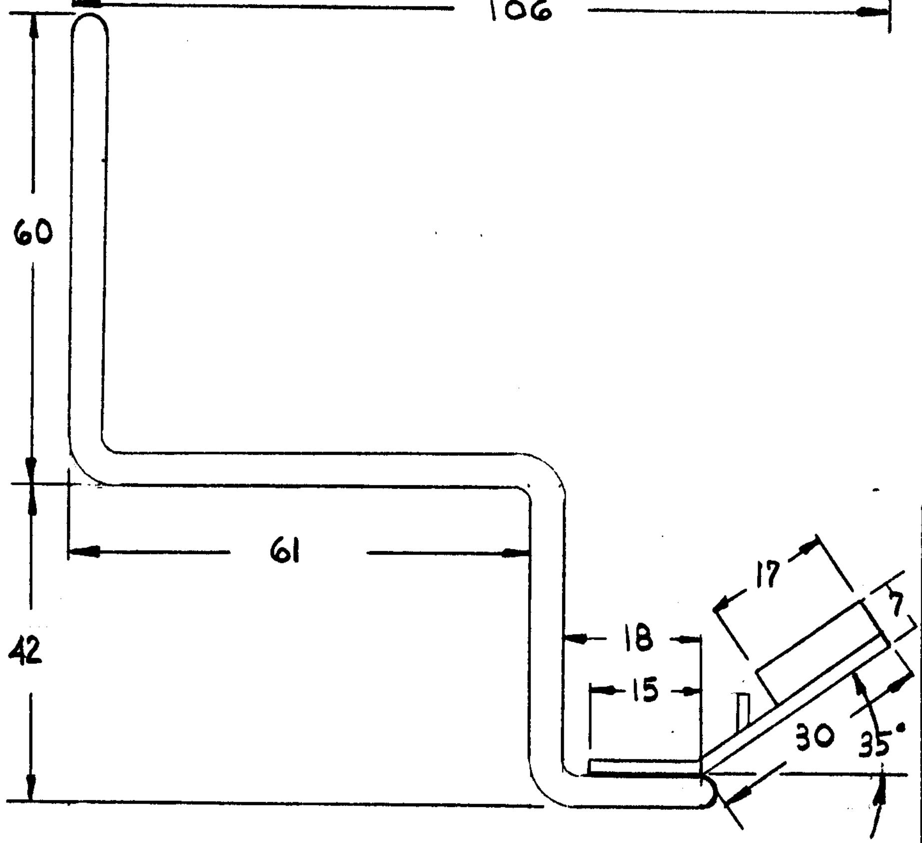


1. TAPERED PIN ASSEMBLY, SEE DETAIL
2. TAPERED PIN ASSEMBLY, SEE DETAIL
3. TAPERED PIN ASSEMBLY, SEE DETAIL
4. DRIVER LINKS L.H. & R.H.
5. LINK PIN ASSEMBLY
6. FLAT WASHERS
7. BUCKET LINK
8. DIPPER END, WITH BUSHINGS
9. BUCKET LINK PIN
10. DIPPERSTICK ASSEMBLY
11. TAPERED PIN ASSEMBLY, SEE DETAIL
12. BOOM ASSEMBLY
13. TAPERED PIN ASSEMBLY, WITH BUSHINGS
14. TAPERED PIN ASSEMBLY, SEE DETAIL
15. BOOM BUSHINGS,

LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: / DATE: 26 FEB 85	APPROVED BY: C. GAMBINO	DRAWN BY C. Gambino / REVISED
BOOM AND DIPPERSTICK ASSEMBLY DRAWING III.		
ME 4182 DESIGN PROJECT		DRAWING NUMBER 3 OF 22







2024 ALUMINUM TUBING, 4 CM O.D.
SEE DETAILS, FOOT SUPPORT 2 CM 2024 AL.
WEBBING. DOW KEVLAR, 6 CM. WIDE

LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1:10	[redacted] BY: J. HOTCHKISS	DRAWN BY Gambino
DATE: 12 MAR 85		REVISED
OPERATOR CHAIR DETAIL		I. A.
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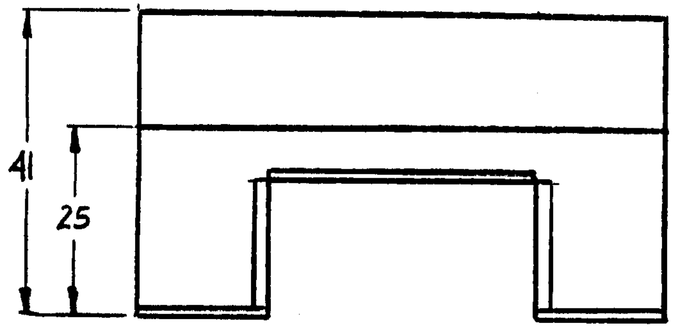
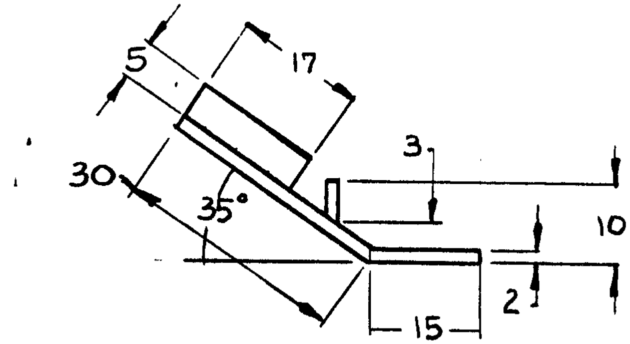
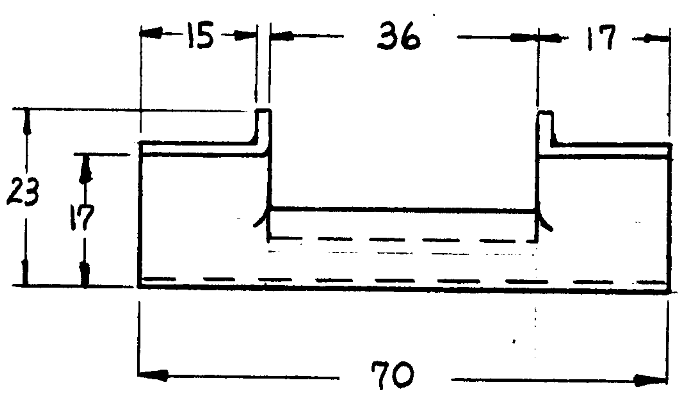
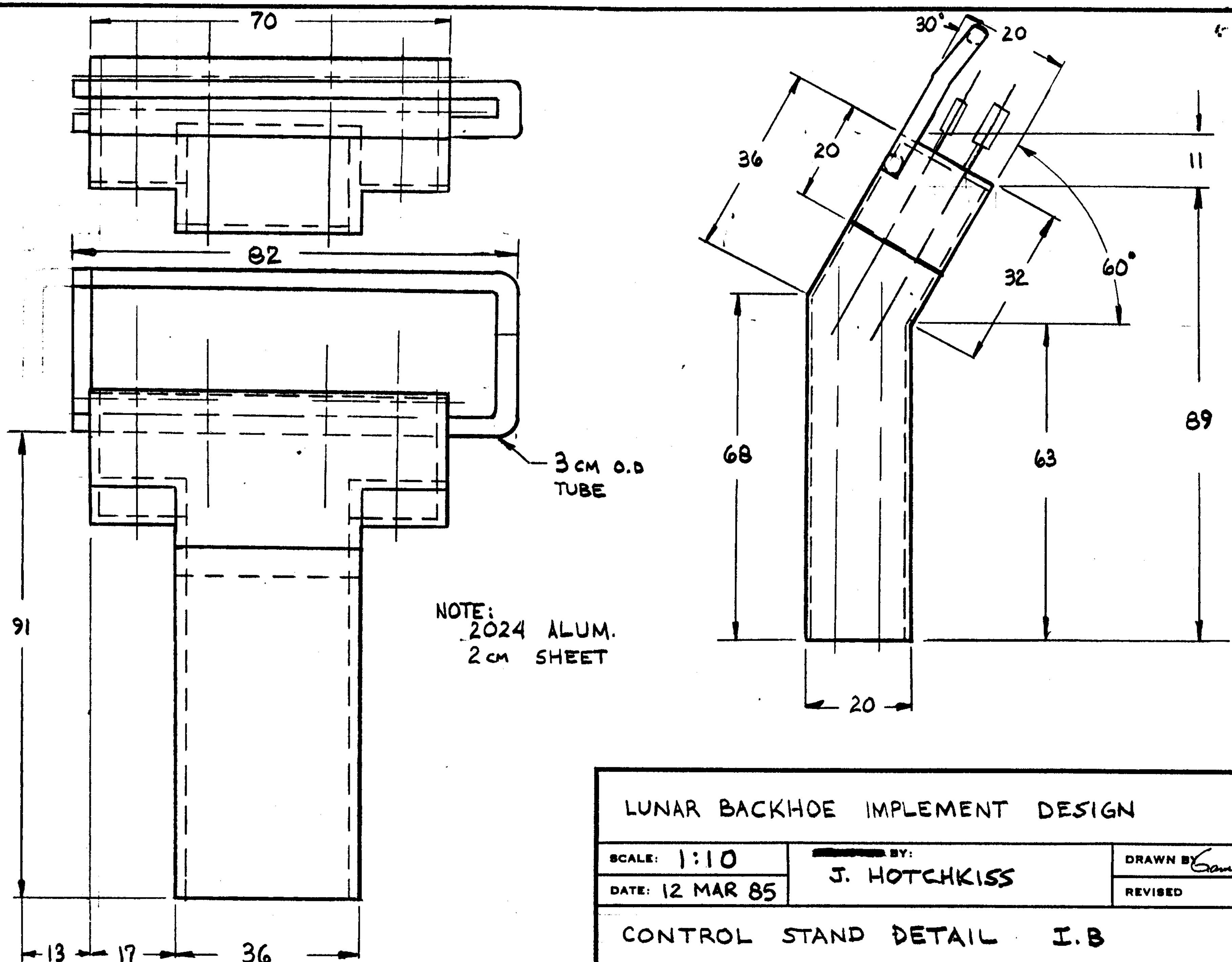






NOTE 2024 ALUMINUM
DIMENSIONS IN CM

LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1:10 DATE: 12 MAR 85	APPROVED BY: J. HOTCHKISS	DRAWN BY [signature] REVISED
FOOT PLATE DETAIL		I. A. 1
ME 4182 TU - 5:30		DRAWING NUMBER 5 OF 22

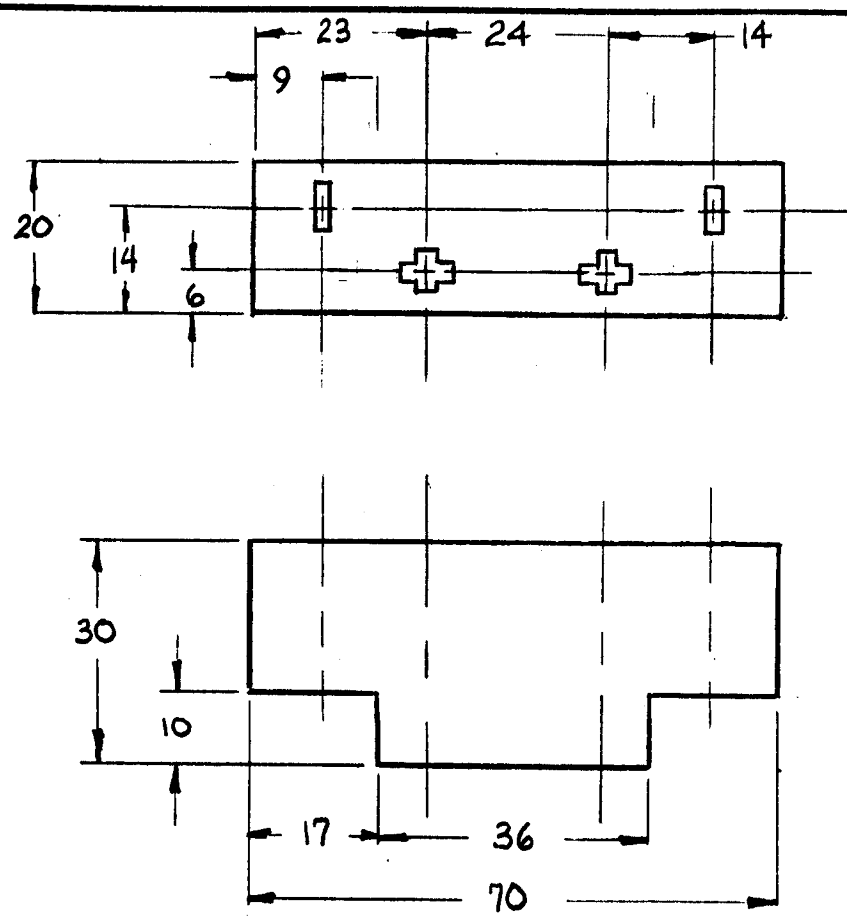


LUNAR BACKHOE IMPLEMENT DESIGN

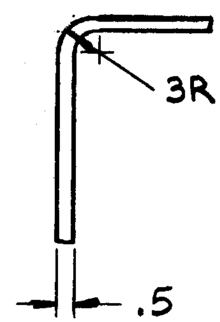
SCALE: 1:10	[redacted] BY: J. HOTCHKISS	DRAWN BY Gambino
DATE: 12 MAR 85		REVISED

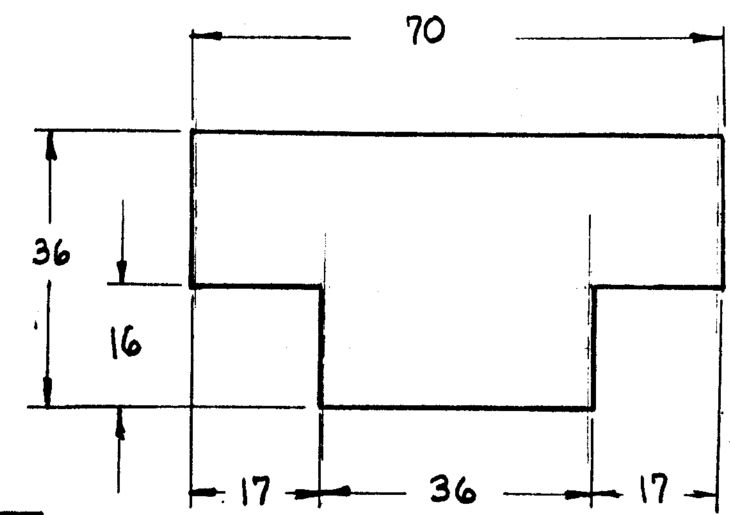
CONTROL STAND DETAIL I.B

ME 4182 TU - 5:30	DRAWING NUMBER 6 OF 22



FRONT COVER





BACK COVER

2024 ALUMINUM

DIMENSIONS IN CM

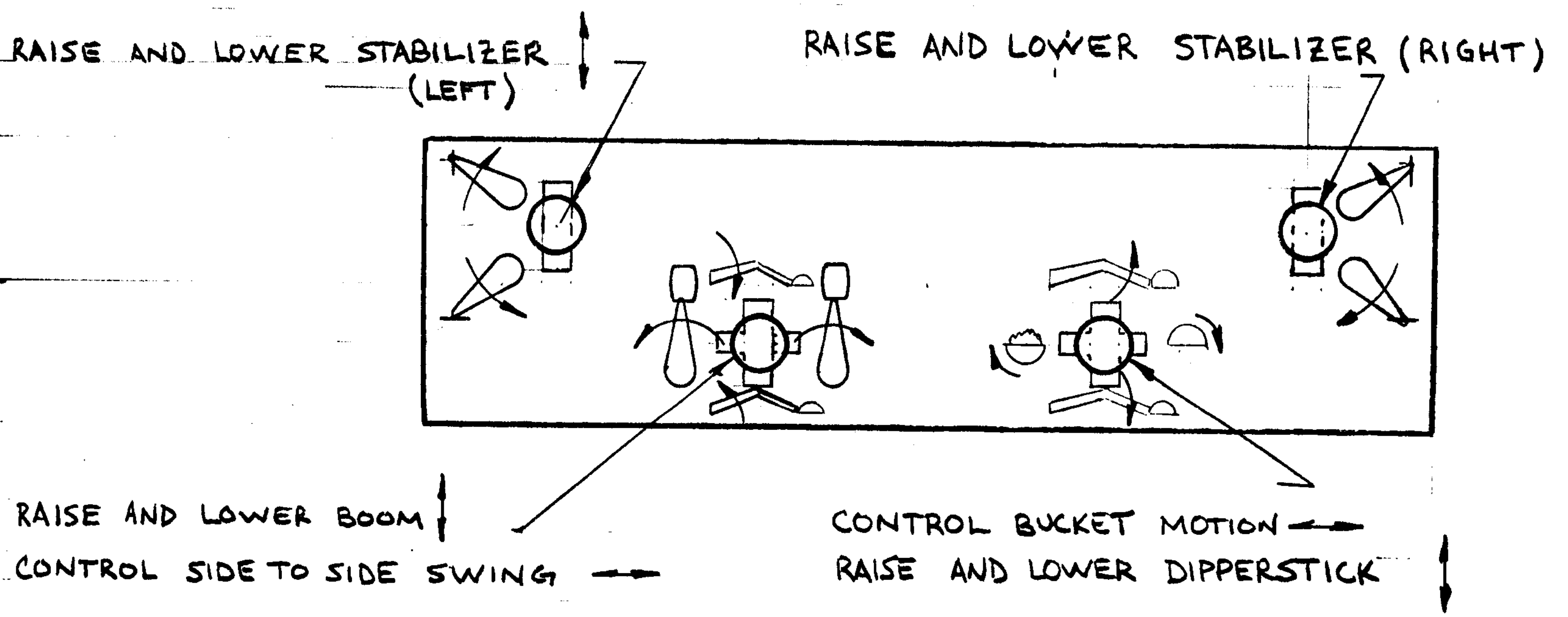
TOLERANCE

SECURED WITH BOLTS
(SEE SCHEDULE)

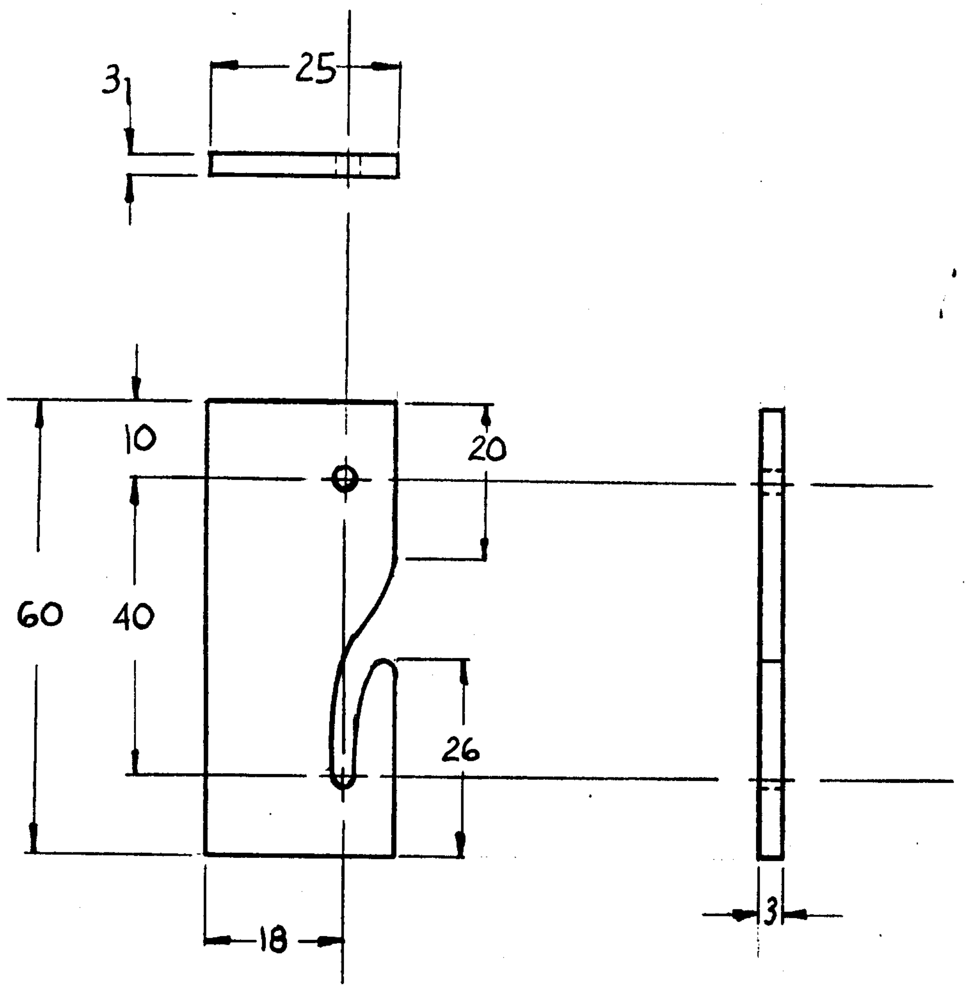
LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1:10 DATE: 12 MAR 85	[redacted] BY: J. HOTCHKISS	DRAWN BY Gambino REVISED
CONTROL STAND DETAILS , I.B1., I.B.2		
ME 4182 TU-5:30		DRAWING NUMBER 7 & 8 OF 22

8½ X 11 PRINTED ON NO. 1000H CLEARPRINT

10

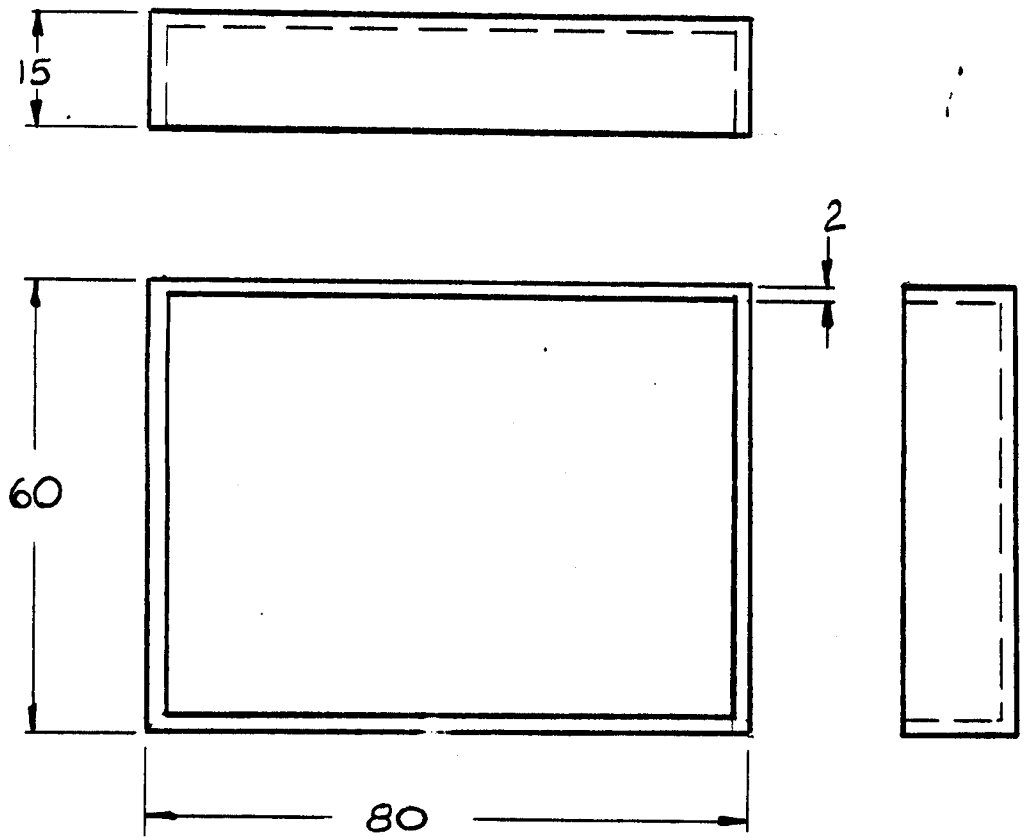


LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1:5 DATE: 12 MAR 85	[redacted] BY: J. HOTCHKISS	DRAWN BY Gambino REVISED
CONTROL GRAPHIC DETAIL I. B. 3		
ME 4182 TU - 5:30		DRAWING NUMBER 9 OF 22



NOTE: DIMENSIONS IN CM
QTY. 2
2024 ALUMINUM

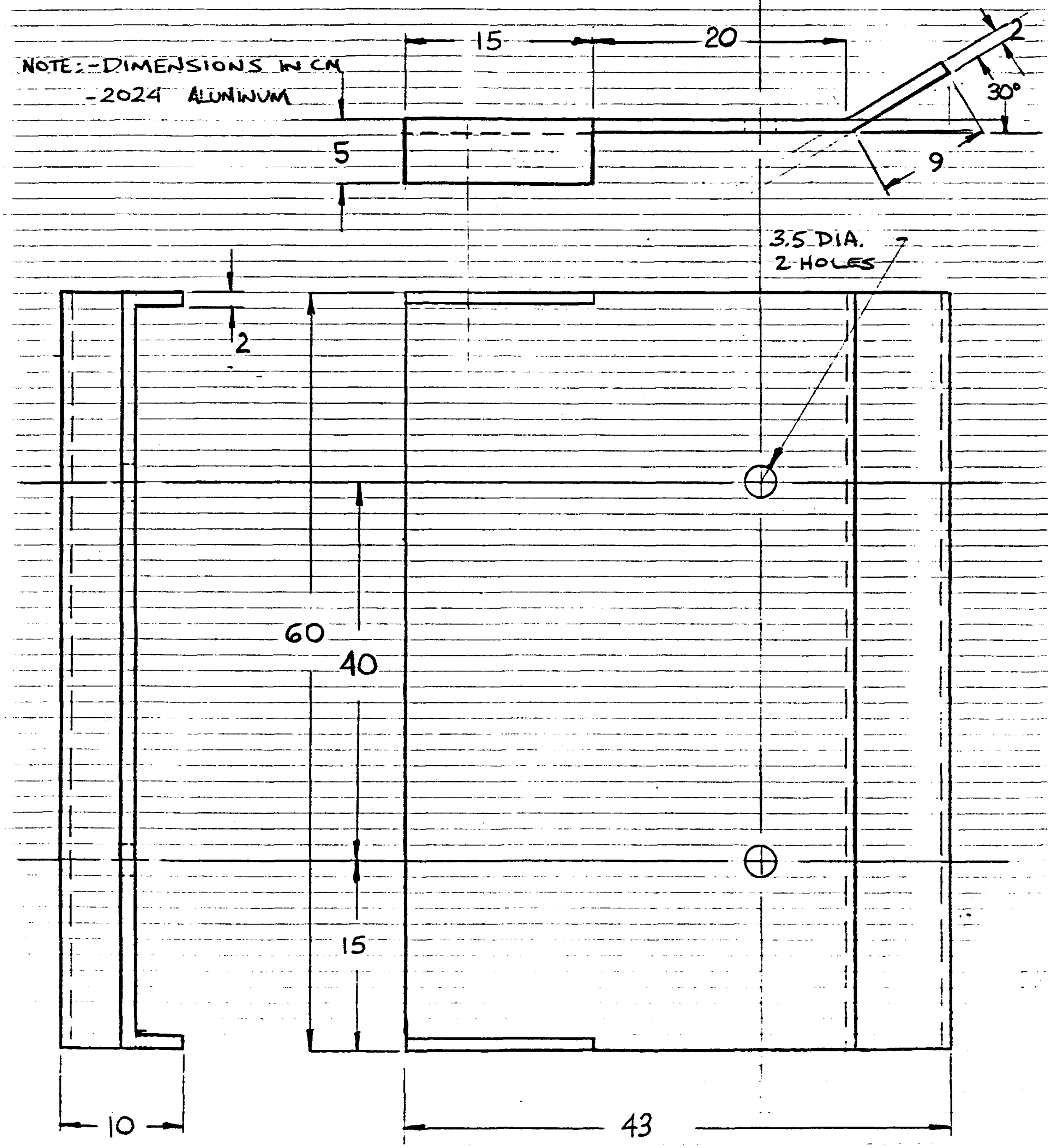
LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1:10 / DATE: 12 MAR 85	APPROVED BY: J. HITCHCOCK	DRAWN BY Gambino / REVISED
DOZER MOUNT		II. A.
ME 4182 TU - 5:30		DRAWING NUMBER 10 OF 22



DIMENSIONS IN CM
2 CM 2024 ALUMINUM

LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1:10 DATE: 12 MAR 85	[redacted] BY: J. HITCHCOCK	DRAWN BY Gambino REVISED
IMPLEMENT MOUNT BOX		II.B.1
ME 4182 TU - 5:30		DRAWING NUMBER 11 OF 22

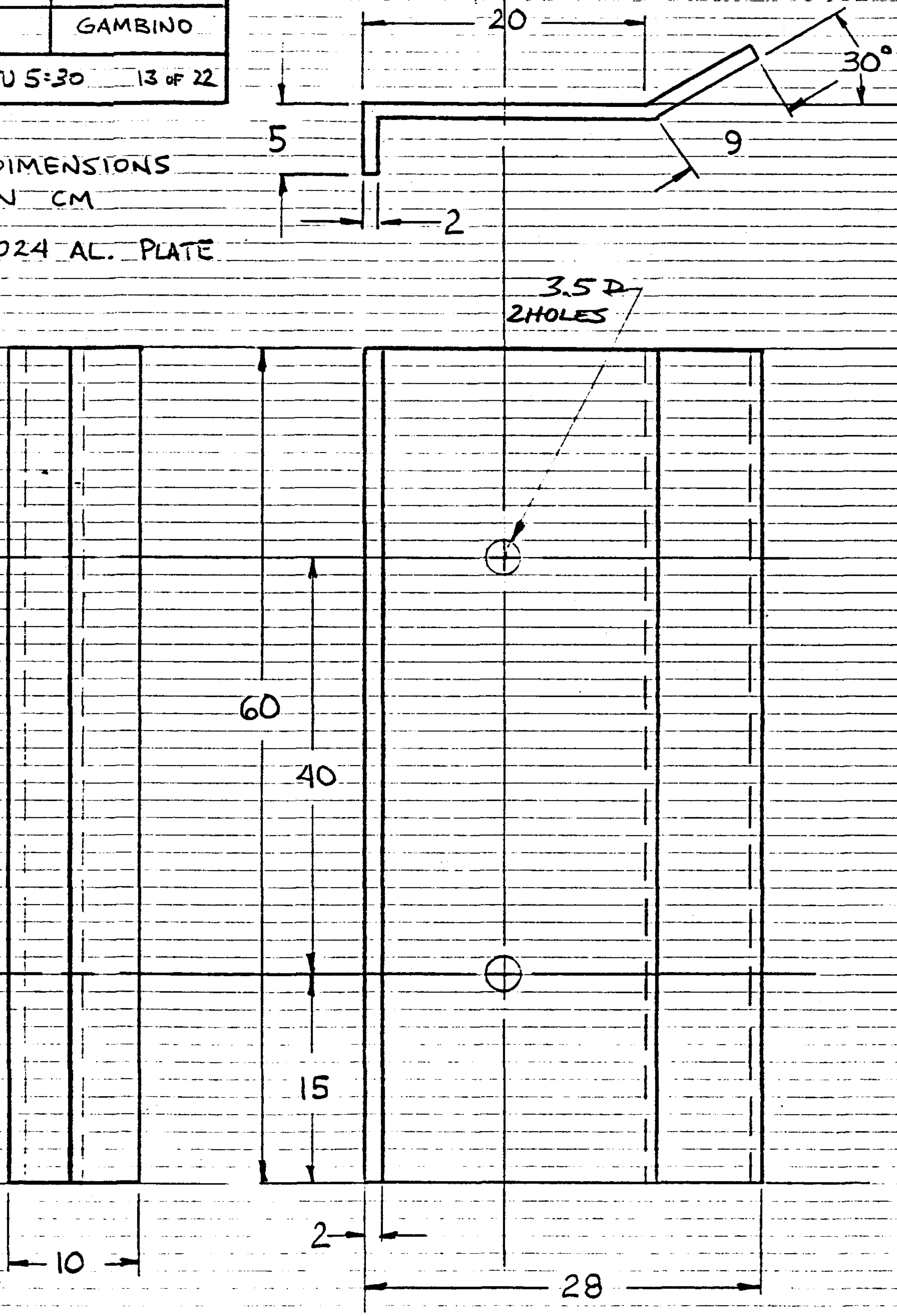
LUNAR BACKHOE IMPLEMENT	
OUTBOARD PLATE II B.2.	
1:10 SCALE	12 MAR 85
HITCOCK	GAMBINO
ME 4182 TU 5:30	12 OF 22

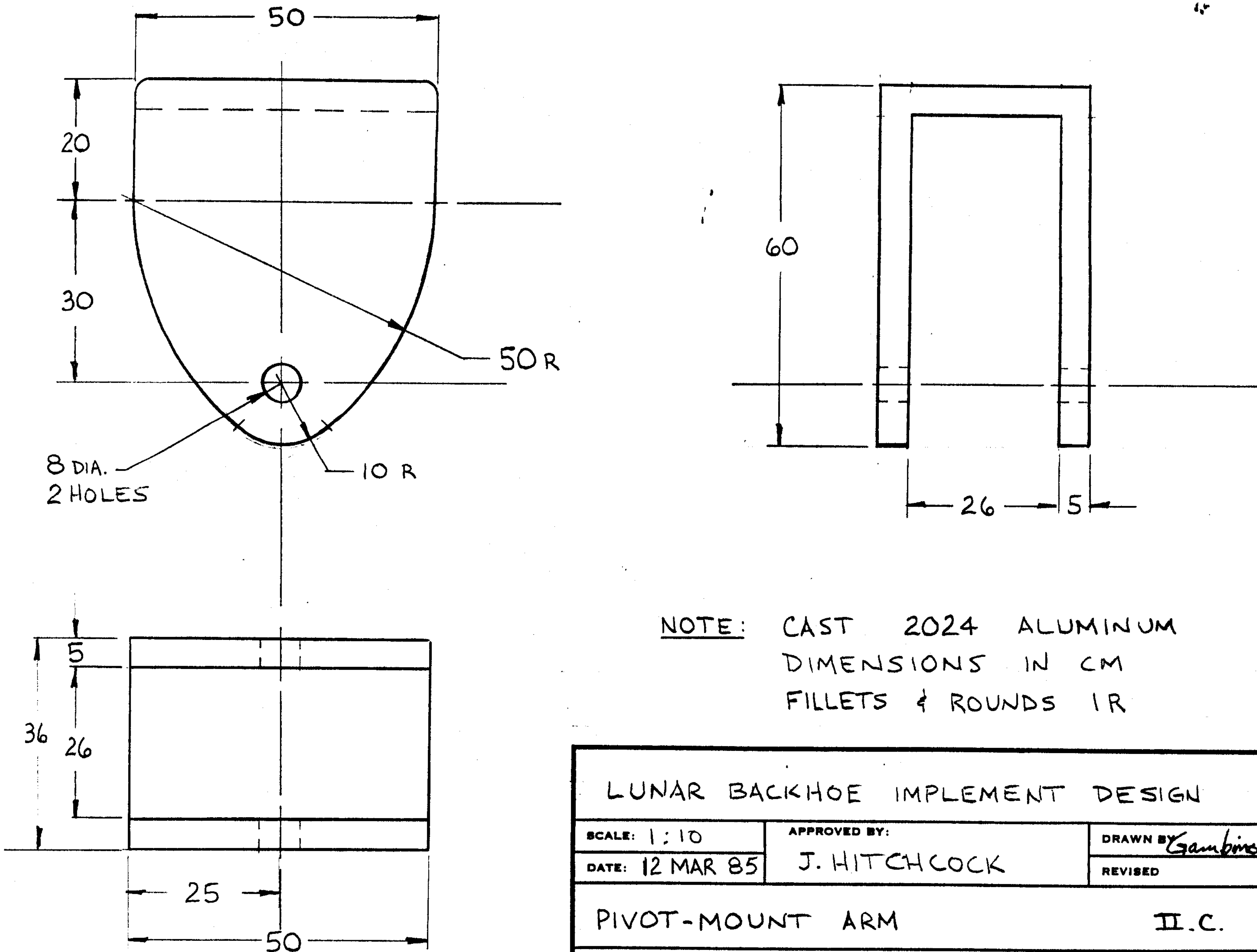


LUNAR BACKHOE IMPLEMENT	
INBOARD PLATE DETAIL II.B.3	
1:10 SCALE	12 MAR 85
HITCHCOCK	GAMBINO
ME 4182 TU 5:30	13 OF 22

NOTE: - DIMENSIONS IN CM

- 2024 AL. PLATE

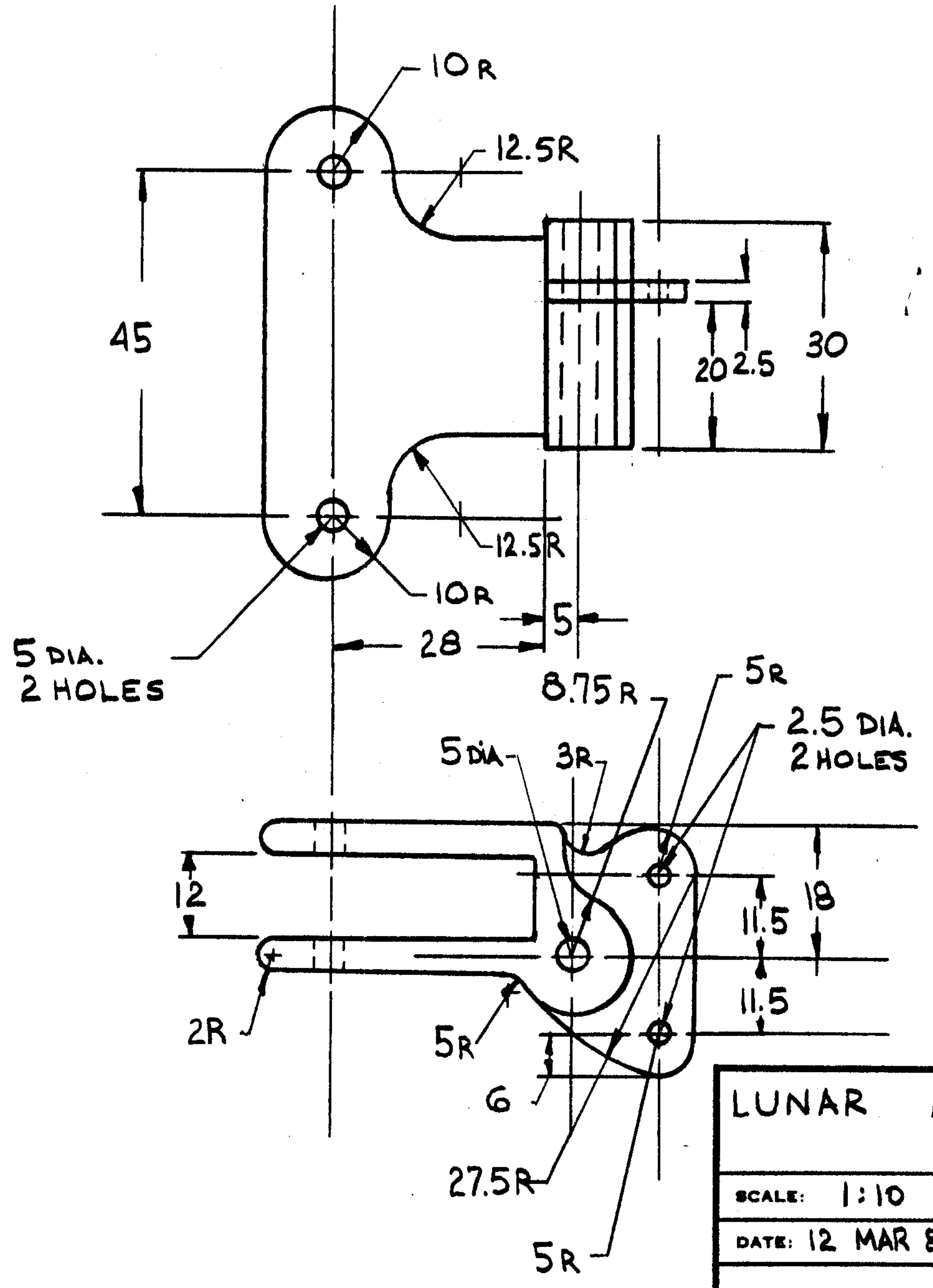


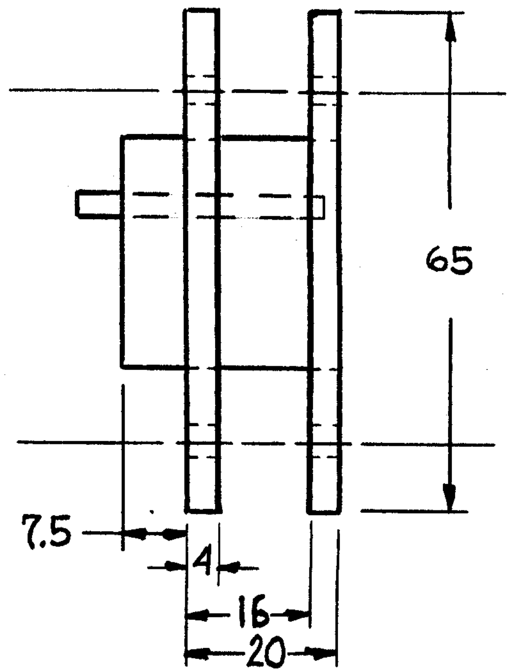


NOTE: CAST 2024 ALUMINUM
DIMENSIONS IN CM
FILLETS & ROUNDS 1R

LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1 : 10 / DATE: 12 MAR 85	APPROVED BY: J. HITCHCOCK	DRAWN BY Gambino / REVISED
PIVOT-MOUNT ARM		II.C.
ME 4182 TU - 5:30		DRAWING NUMBER 14 OF 22

8½ X 11 PRINTED ON NO. 1000H CLEARPRINT





NOTE: CAST 2024 ALUMINUM
QTY. 1
DIMENSIONS IN CM

LUNAR BACKHOE IMPLEMENT DESIGN

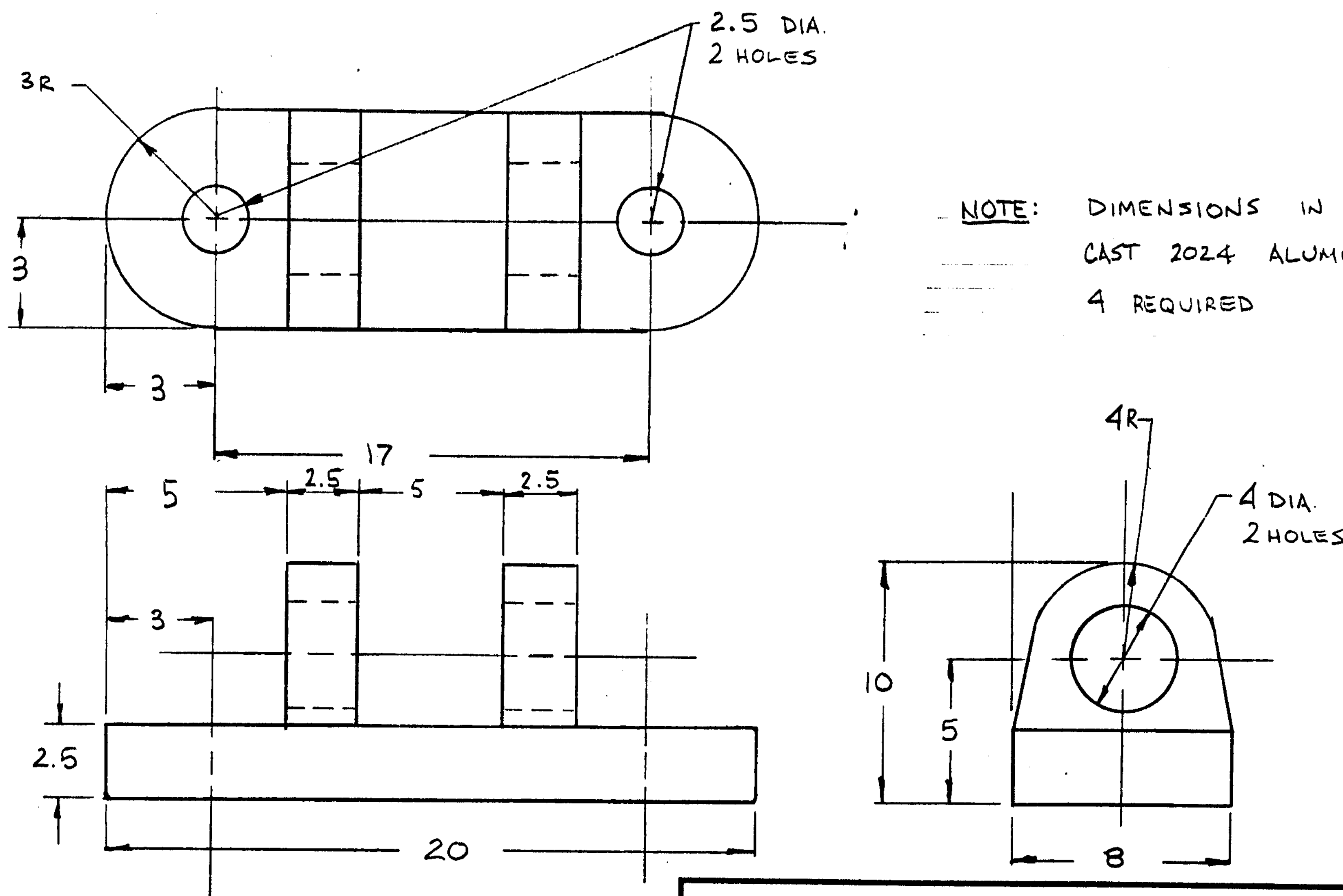
SCALE: 1:10
DATE: 12 MAR 85
[redacted] BY: J. HITCHCOCK
DRAWN BY: Sambino
REVISED

PIVOT - MOUNT
II.D

ME 4182 TU - 5:30
DRAWING NUMBER 15 OF 22

8½ X 11 PRINTED ON NO. 1000H CLEARPRINT

10

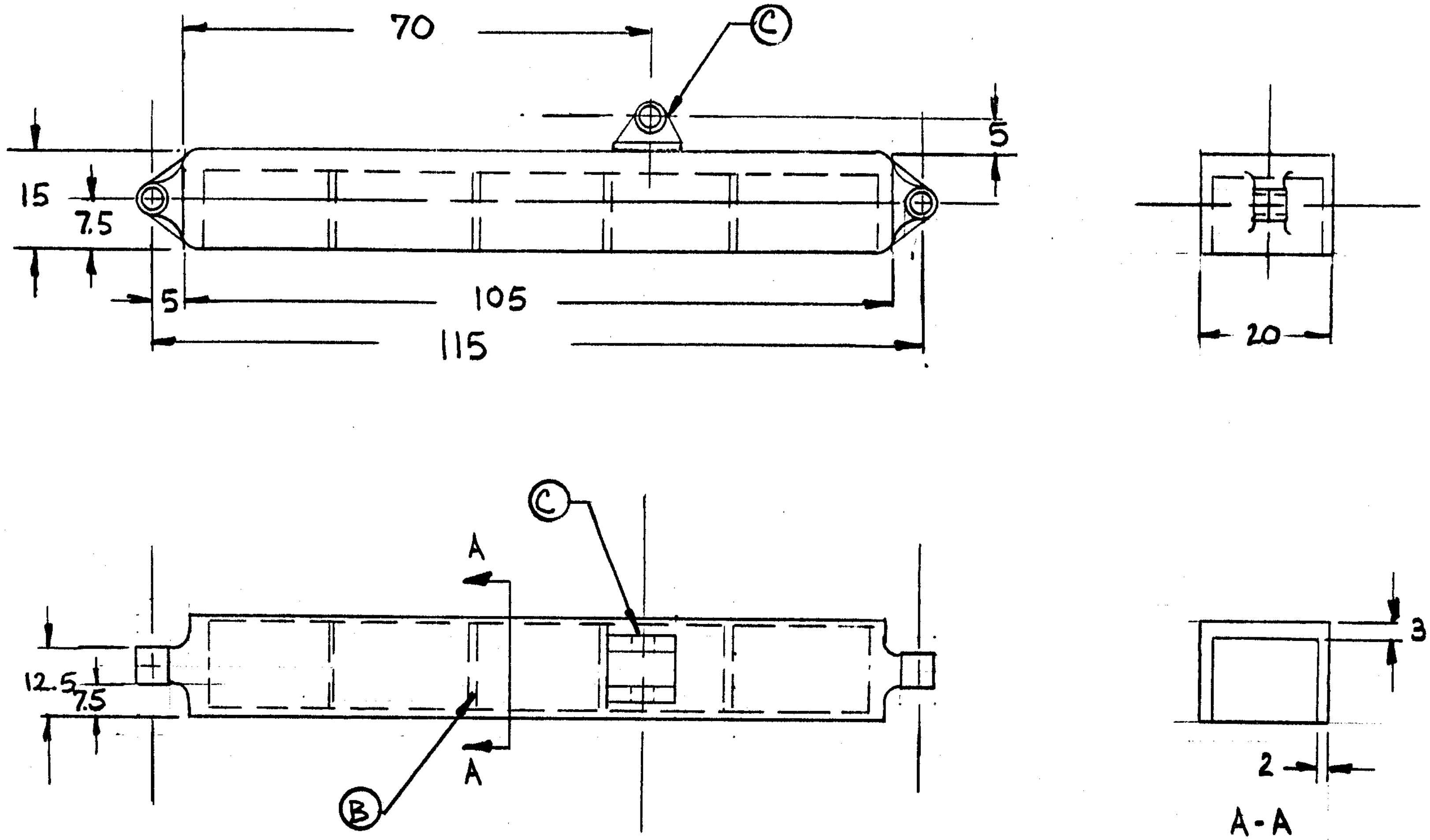


NOTE: DIMENSIONS IN CM
CAST 2024 ALUMINUM
4 REQUIRED

LUNAR BACKHOE IMPLEMENT DESIGN

SCALE: 1 : 2	APPROVED BY: J. HITCHCOCK	DRAWN BY: Gambino
DATE: 12 MAR 85		REVISED
STABILIZER / CYLINDER MOUNT		II. E
ME 4182 TU - 5:30		DRAWING NUMBER 16 OF 22

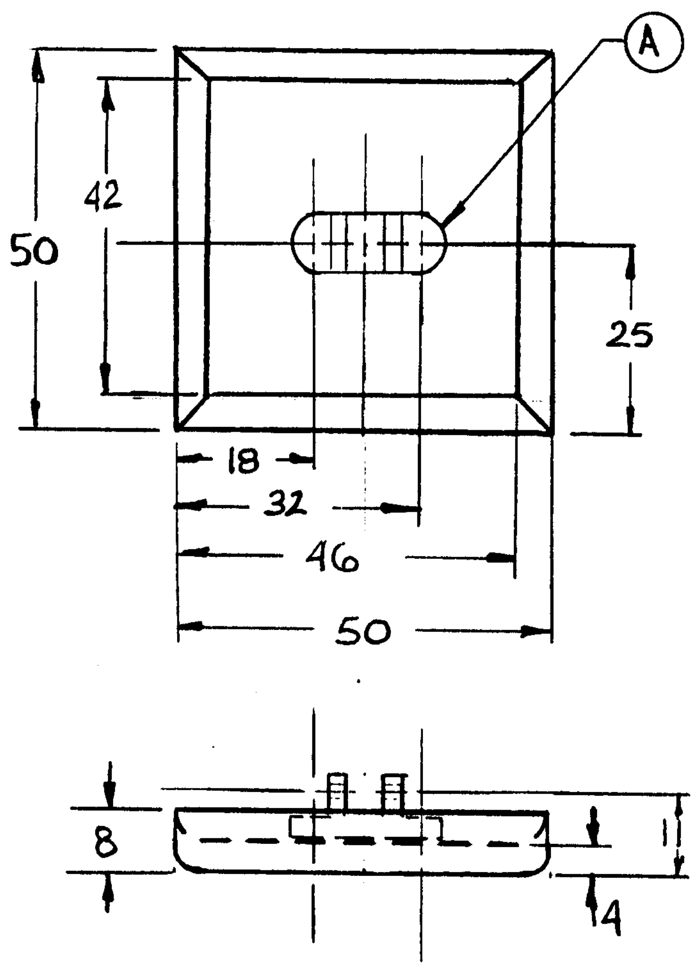
8½ X 11 PRINTED ON NO. 1000H CLEARPRINT



NOTE:
DIMENSIONS IN CM
(B) 4 2 CM RIBS, 20 CM SPACING
(C) PART NO.
SEE DETAIL NO. II.E
2024 ALUM. CAST, 2 REQD.

LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1:10 DATE: 12 MAR 85	[redacted] BY: C. GAMBINO	DRAWN BY Gambino REVISED
STABILIZER ARM DETAIL II.F		
ME 4182 TU-5:30		DRAWING NUMBER 17 OF 22

8½ X 11 PRINTED ON NO. 1000H CLEARPRINT

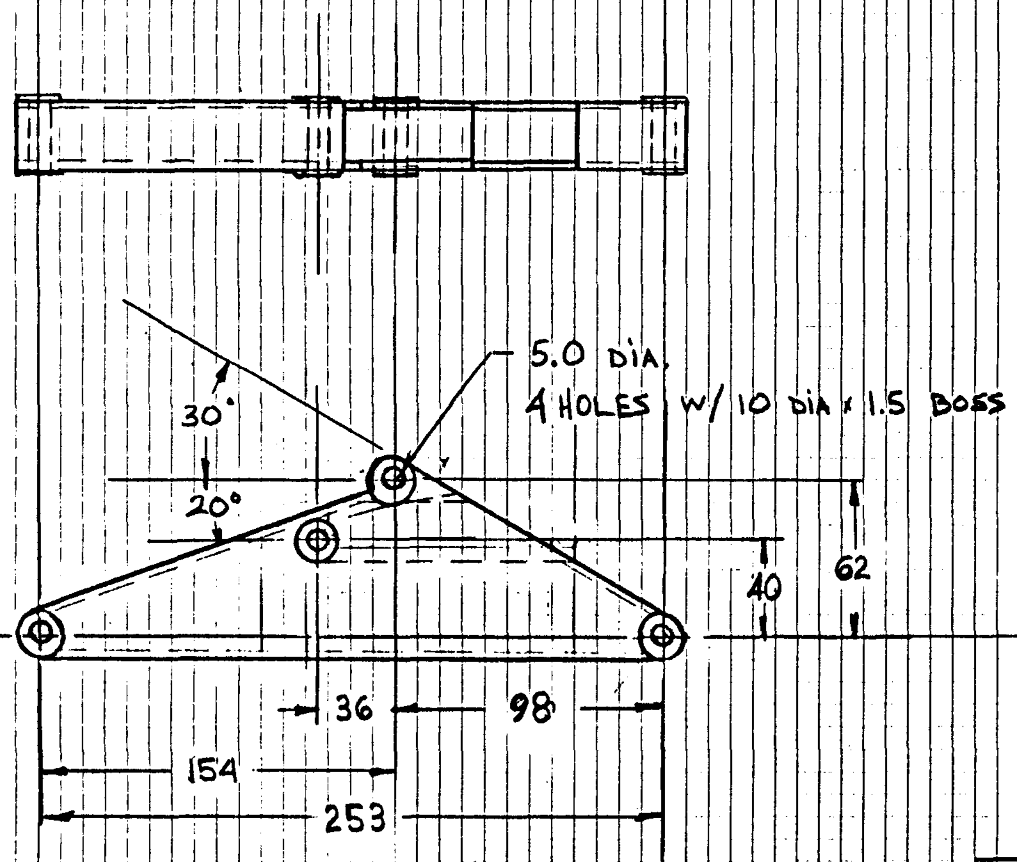


NOTES: 2024 ALUM. CAST , 2 REQD.

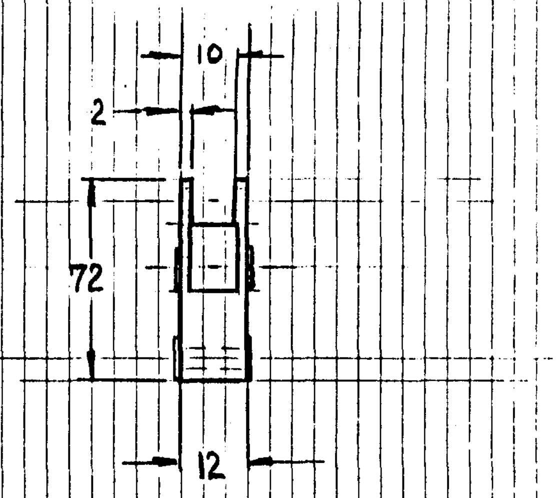
(A) PART NO.
SEE DETAIL NO
DIMENSIONS IN CM

LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: 1:10	[redacted] BY: C. GAMBINO	DRAWN BY Gambino
DATE: 12 MAR 82		REVISED
STABILIZER PAD DETAIL		II. G
ME 4182 TU - 5:30		DRAWING NUMBER 18 OF 22

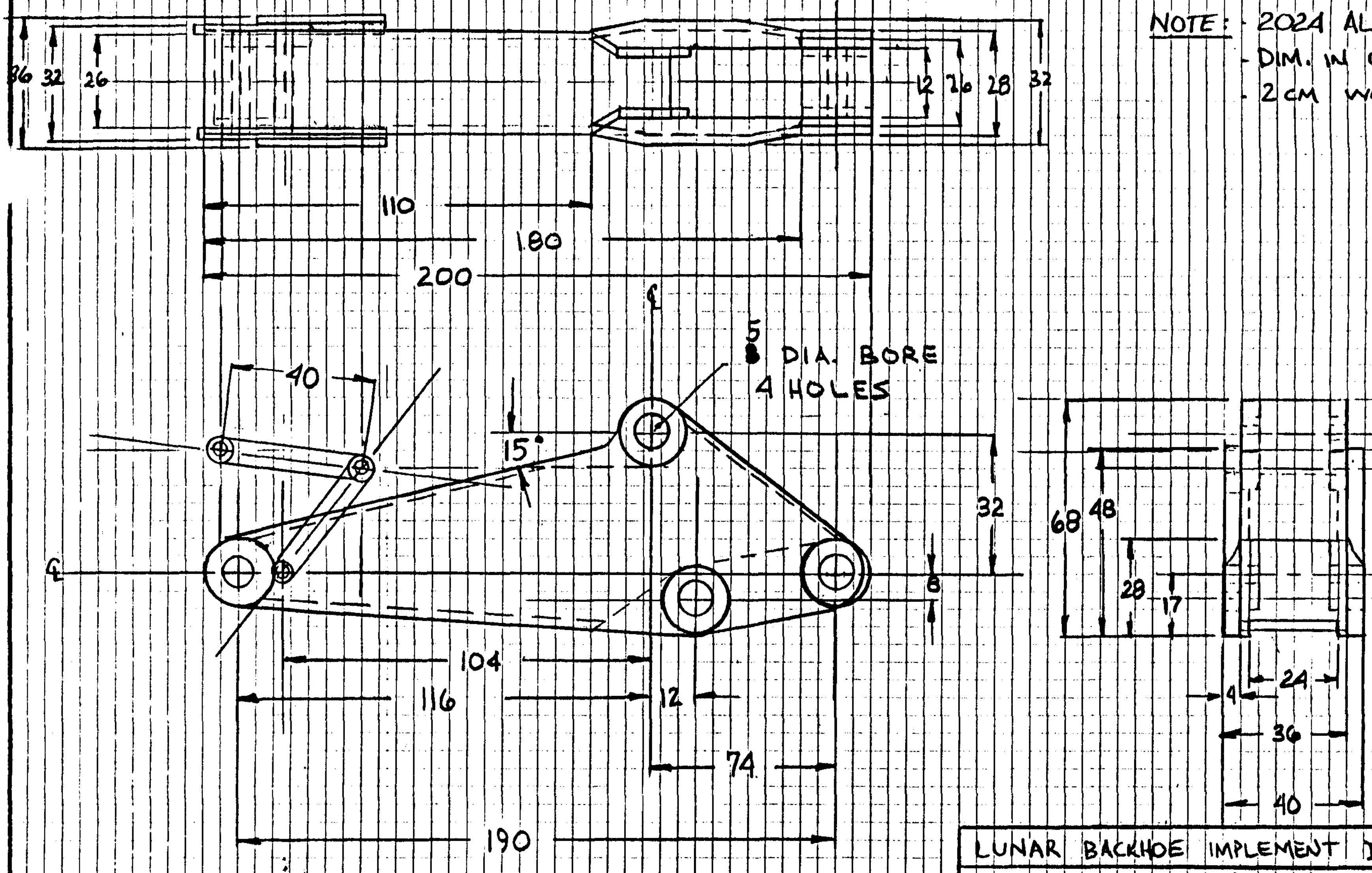
8½ X 11 PRINTED ON NO. 1000H CLEARPRINT



NOTE: - CAST 2024 ALUMINUM
- DIMENSIONS IN CM
- WALL THICKNESS: 2 CM
- NOT TO SCALE



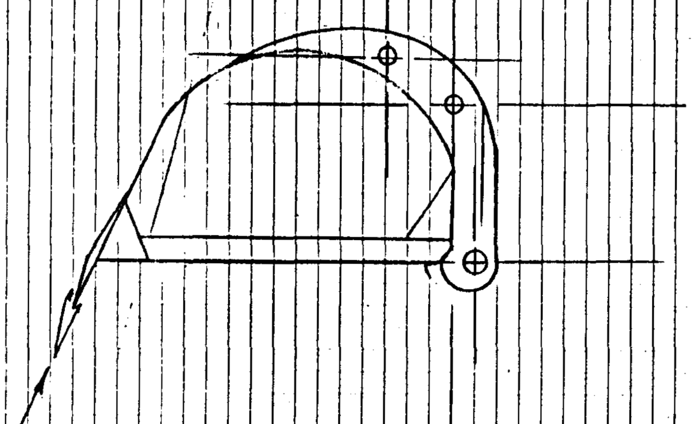
LUNAR BACKHOE IMPLEMENT DESIGN		
1:10 SCALE / 12 MAR 85	C. GAMBINO	C. Gambino
BOOM DETAIL		III. A.
ME 4182 TU 5:30		19 OF 22

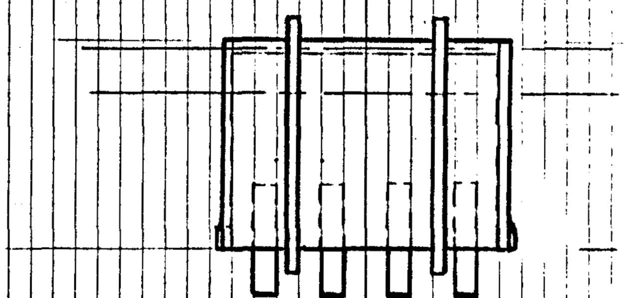


NOTE: - 2024 ALUM. CAST
- DIM. IN CM
- 2 CM WALL THICKNESS

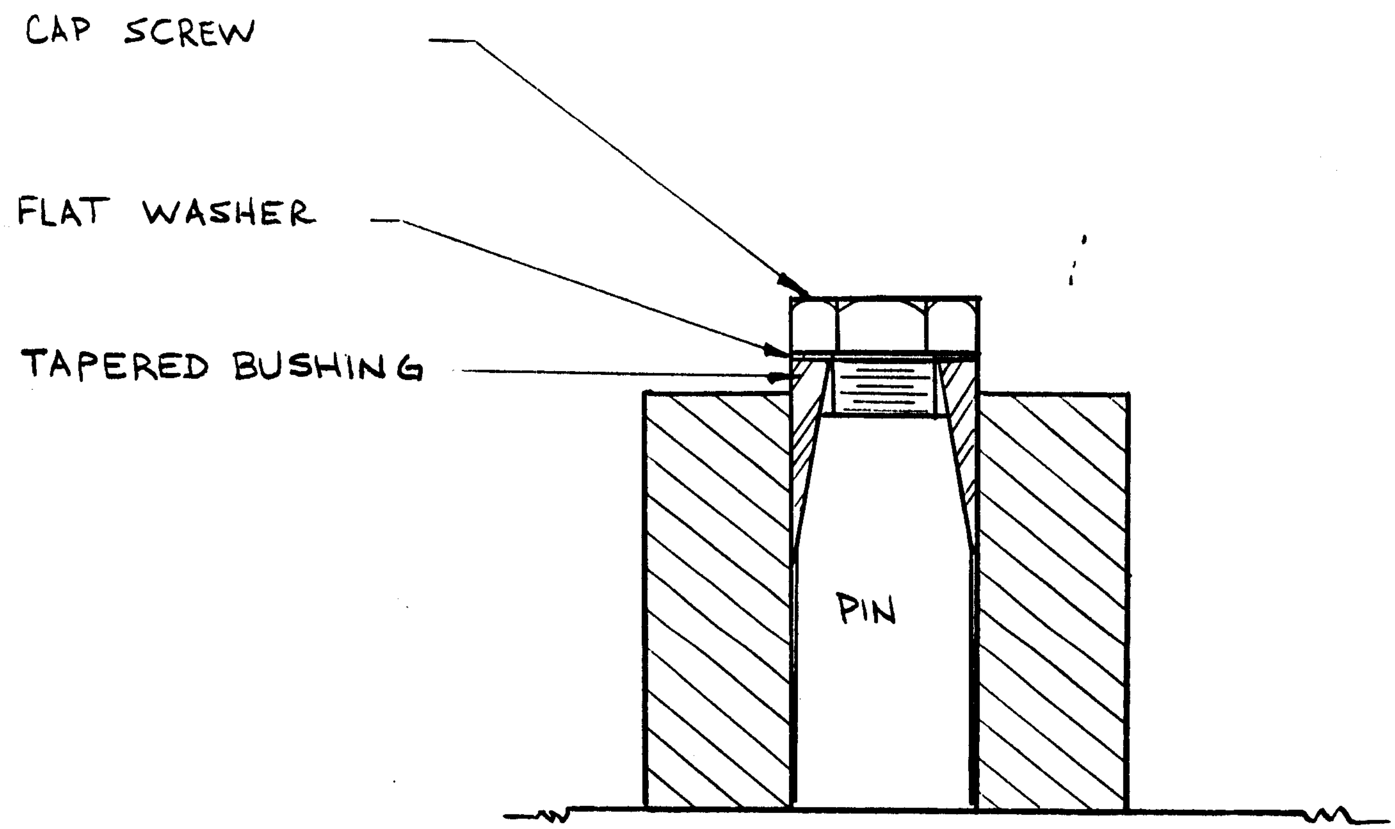
LUNAR BACKHOE IMPLEMENT DESIGN	
DIPPERSTICK DETAIL	III. B
12 MARCH 85	C. GAMBINO
ME 4182 TU 5:30	20 OF 22

NOTE:
- DEERE & CO. DESIGN
- CAST STEEL
- 610 mm WIDTH





LUNAR BACKHOE IMPLEMENT DESIGN		
1:10	DEERE & CO. DESIGN	Gambino
12 MARCH 85		
BUCKET DETAIL		III. C
ME 4182	TU 5:30	21 OF 22



LUNAR BACKHOE IMPLEMENT DESIGN		
SCALE: — / DATE: 12 MAR 85	APPROVED BY: C. GAMBINO	DRAWN BY Gambino / REVISED
TAPERED PIN ASSEMBLY DETAIL III.D.		
ME 4182 TU - 5:30		DRAWING NUMBER 22 OF 22

NAME	NUMBER	QTY	AVAILABILITY	MATERIAL
OPERATORS CHAIR	1100	1	C	2024 ALUMINIUM
WEBBING	1110	14m	V	KEVLAR
POP RIVETS	1111	60	V	ALUMINUM 2024
CROSS TUBES	1120	2	C	2024 ALUMINUM
FOOT PLATE	1200	1	C	2024 ALUM.
CONTROL STAND	1300	1	C	2024
HAND BAR	1310	1	C	2024
FRONT COVER	1320	1	C	2024
BACK COVER	1330	1	C	2024
BOLTS		12	V	?
VALVE - ASSEMBLY	1400	1	V	-
LEVERS	1410	4	V	-
HANDLES	1411	4	C	-
GRAPHIC DECAL	1500	1	V	-
DOZER MOUNT	2000	1	C	2024
MOUNT BOX	2100	1	C	2024
OUTBOARD PLATE	2200	2 (RH & LH)	C	2024
PIN	2210	4	V	STEEL
INBOARD PLATE	2300	2 (RH & LH)	C	2024
PIVOT - MOUNT ARM	2400	1	C	2024
PIN	2410	1	V	STEEL
PIVOT MOUNT	2500	1	C	2024
STABILIZER MOUNT	2610	6	C	2024
BOLTS	2612	12	V	
STABILIZER ARM	2710 (L.H.)	1	C	2024
	2720 (R.H)	1		2024
STABILIZER PAD	2730 (L.H)	1	C	2024
	2740 (R.H)	1		2024
MANIFOLD	2900	1	V	—
BOOM	3000	1	C	2024
ANCHOR PIN	3010	1	C	STEEL
DIPPERST	3100	1	C	2024

NAME	NUMBER	QTY.	AVAILABILITY	MATERIAL
PIVOT PIN	3110	1	V	STEEL
BUCKET LINK	3201 (LH)	2	C	2024
	3202 (RH)			
PIN - BUCKET LINK	3203	4	C	STEEL
DIPPERSTICK LINK	3300	2	C	2024
PIN (ABOVE)	3301	2	V	STEEL
BUCKET	3400	1	V	ALUM
PIN	3410	1	V	STEEL
TEETH	3420	4	V	STEEL

AVAILABILITY CODE : V : DEERE & CO.
C : TO BE CUSTOM MADE

HOSES: (5000) $\frac{3}{4}$ IN. I.D. TO CYLINDERS & CONTROLS
$1\frac{1}{2}$ IN I.D. TO PRIME MOVER
WIRE BRAID, INSULATED, FOIL WRAPPED

COUPLINGS (6000) STANDARD FITTINGS AS REQUIRED

CYLINDERS (4000) AS PER JOHN DEERE
MODEL 9550 WITH EXPANDING
BOOTS OVER RODS

LUBRICANT (8000) MOLYBDENUM DISULFIDE

FLUID (7000) SYNTHETIC PETROLEUM BASE
SAE STANDARD

Cylinder Sizes:

Qty.	Cylinder	Bore	Stroke	Rod Diameter
1	Boom	102 mm	822 mm	51 mm
1	Crowd	89 mm	794 mm	44 mm
1	Bucket	76 mm	673 mm	44 mm
2	Swing	89 mm	226 mm	44 mm
2	Stabilizer	89 mm	394 mm	44 mm

· RODS ARE GROUND , HEAT TREATED , PLATED , POLISHED

Pin Sizes:

	Qty.	Total Length	Diameter
	8	12 cm.	5 cm
	8	10 cm	4 cm
	4	6 cm	3 cm
	1	36 cm	8 cm
	4	5 cm	2.5 cm
TOTAL	25 PINS		

REQUIRES : 50 FLAT WASHERS
50 TAPERED BUSHINGS

Appendix

ME 4182 WEEKLY PROGRESS REPORT

PERIOD: 7 January THRU: 14 January TEAM NO.: TU 5:30

TITLE: Design of a Lunar Backhoe Implement

COMMENTS: Our first week as a group was essentially organizational. We determined who was to be a group leader and exchanged information about how to contact each other. Our project is to design a backhoe which can be transported to the moon by a space shuttle, and can be used on the lunar surface as an aid to constructing a space station. This project was initiated by NASA and refined by Dr. Brazell. Our immediate problem was lack of information about the moon, the shuttle, backhoes, and requirements and specifications from NASA. We began by assigning areas of particular research to each group member. We planned our next meeting to include exchanging information, brainstorming for ideas, and determing new duties.

NAME, INITIALS	HOURS ENGINEERING	TECHNICIAN	CLERICAL	TOTAL
1) Emerick, J.	-	-	10	10
2) Gambino, C.	-	-	8	8
3) Hitchcock, J.	-	-	7	7
4) Hotchkiss, J.	-	-	9	9
5) Rinz, W.J.	-	-	8	8
6)				
TOTALS =			42	42

ME 4182 WEEKLY PROGRESS REPORT

PERIOD: January 15 THRU: January 21 TEAM NO.: TU 5:30

TITLE: Design of a Lunar Backhoe Implement

COMMENTS:

Research was done to educate the members of the group. The topics researched included earth construction equipment, NASA lunar surface; lunar base; lunar surface travel; and lunar rover research reports. Outside vendors were also contacted for their manufactured equipment specifications. Our brainstorming yielded ideas of equipment resembling draglines, blowers, vacuums, and lunar surface solidifiers.

NAME, INITIALS	HOURS ENGINEERING	TECHNICIAN	CLERICAL	TOTAL
1) Emerick, J.	-	-	8	8
2) Gambino, C.	-	-	9	9
3) Hitchcock, J.	-	-	9	9
4) Hotchkiss, J.	-	-	8	8
5) Rinz, W.J.	-	-	8	8
6)				
TOTALS =			42	42

ME 4182 WEEKLY PROGRESS REPORT

PERIOD: January 22 THRU: January 29 TEAM NO.: TU 5:30

TITLE: Design of a Lunar Backhoe Implement

COMMENTS:

At our weekly meeting, we expressed a need for more extensive research of the literature. The topics which we are continuing are:

1. ergonomic design of control panel
2. power requirements
3. hydraulic cylinder requirements
4. materials
5. force requirements
6. current backhoe designs
7. any additional paramenters

We are assuming that we are going to be getting some information from NASA which will aid us in our literature search.

NAME, INITIALS	HOURS ENGINEERING	TECHNICIAN	CLERICAL	TOTAL
1) Emerick, J.	-	-	9	9
2) Gambino, C.	-	-	10	10
3) Hitchcock, J.	-	-	9	9
4) Hotchkiss, J.	-	-	10	10
5) Rinz, W.J.	-	-	11	11
6)				
TOTALS =	-	-	49	49

ME 4182 WEEKLY PROGRESS REPORT

PERIOD: 29 January THRU: 05 February TEAM NO.: TU- 5:30

TITLE: Design of a Lunar Excavator

COMMENTS: The technical literature search continues. The Georgia Tech Library remains the primary source of information. The topics under investigation include; the man-machine interface, materials, hydraulic systems and other power sources, testing and evaluation procedures, force requirements, controlling devices, methods of attachment to a primary mover.

The report outline has been prepared and submitted along with this report.

In the coming week a specific design idea will be selected and the solution to the problems entailed will begin.

Along with the creative input, the areas of responsibility of each team member is as follows:

Emerick, J.- materials and effects of radiation
Gambino, C.- use of hydraulics and alternatives
Hitchcock, J.- possible test procedures and lunar surface
Hotchkiss, J.- man-machine interface, space suits
Rinz, W.- force requirements, materials, radiation effects, report outline

NAME, INITIALS	HOURS ENGINEERING	TECHNICIAN	CLERICAL	TOTAL
1) Emerick, J.		1	6	7
2) Gambino, C.		1	6.5	7.5
3) Hitchcock J.		1	6	7
4) Hotchkiss, J.		1	7	8
5) Rinz, W.		1	7	8
6)				
TOTALS =		5	32.5	37.5

ME 4182 WEEKLY PROGRESS REPORT

PERIOD: 6 FEBRUARY THRU: 19 FEBRUARY TEAM NO.: TU-5:30

TITLE: Design of a Backhoe Implement for Lunar Excavation

COMMENTS: The 12 February meeting was cancelled due to inclimate weather. There were three lengthy group meetings conducted during this period to consolidate research information and to make design decisions.

It has been determined that the final design will be that of an implement which can be attached to a prime mover. The prime mover will be the dozer and attachment will be to the rear end. A communications link has been established with the dozer design group to avoid compatability problems.

The primary areas of responsibility of the individual group members are as follows:

Emerick,J.- materials, coatings, patent information, report format
Gambino,C.- hydraulic specs., force analysis, drawings, progress rep.
Hitchcock,J.- implement-dozer interface, possible use of composites
Hotchkiss,J.- controls, environmental conditions, Ergonomics
Rinz, W.J.- pin lubrication, maintenance, computer programming

In the coming week the design will be such that specific problems can be addressed and solved so that work on the final drawings may begin. The literature will be assembled so that the work on the rough draft of the report may begin as well.The drawings are to be submitted by 26 February, the rough draft by 5 March.

NAME, INITIALS	HOURS ENGINEERING	TECHNICIAN	CLERICAL	TOTAL
2. 1) Emerick, J.		12	8	20
2) Gambino, C.	2	8	10	20
3) Hitchcock, J.	4	7	9	20
4) Hotchkiss, J.	4	8	10	22
5) Rinz, W.J.	4	9	8	21
6)				
TOTALS =	14	44	45	103

ME 4182 WEEKLY PROGRESS REPORT

PERIOD: 19 February THRU: 26 February TEAM NO.: TU 5:30

TITLE: Design of a Lunar Backhoe Implement

COMMENTS: Progress has been impeded by the clerical activities associated with the specifications of the design solution. The group: contact between ourselves and the dozer groups has been difficult to arrange. This has made it impossible to develop a complete solution to the problem of the implement-dozer interface. As a result there was not sufficient information available to start the final drawings in order that they may be finished by 26 February. It is expected that the drawings will be complete by 28 February.

The assembly of materials necessary to complete the rough draft of the report has begun. No delays in the completion of the draft are expected. Contact has been made with area vendors so that part numbers and specifications can be obtained.

The integration of the computer for use in the analysis of this and similar designs is developing well and will be completed by the report due date.

NAME, INITIALS	HOURS ENGINEERING	TECHNICIAN	CLERICAL	TOTAL
1) Emerick,J.	3	0	15	18
2) Gambino,C.	4	4	13	21
3) Hitchcock,J.	5	5	6	16
4) Hotchkiss,J.	7	0	5	12
5) Rinz,W.J.	6	0	6	12
6)				
TOTALS =				

RECORD OF INVENTION - Part I

This is an important legal document. Read instructions carefully before filling in data.

PROJECT NO. ____________

CONTRACT NO. ____________ RECOMMENDED SECURITY CLASSIFICATION ____________ REC. OF INV. NO. ____________

1. NAME OF INVENTOR
John J. Emerick, Jr.
POSITION
student

2. DEPARTMENT OR DIVISION
Mechanical Engineering, Georgia Tech

3. DATES OF EMPLOYMENT
6/81 to 6/85

4. PRESENT ADDRESS (No. Street, City, County, State)
Georgia Tech Box 33165, Atlanta, GA 30332
TELEPHONE
355-3191 (816)
PERMANENT OR UNTIL
6-85

5. PERMANENT ADDRESS (No. Street, City, County, State)
2203 Crestline Dr., Kirksville, MO 63501
TELEPHONE
(816) 665-3457

6. NAMES (S) AND ADDRESS (ES) OF CO-INVENTORS (If any)
Chris Gambino
Jim Hitchcock
John Hotchkiss Bill Rinz

7. DESCRIPTIVE TITLE OF INVENTION
Lunar Excavator

8. LIST DRAWINGS, SKETCHES, PHOTOS, REPORTS, DESCRIPTIONS, NOTEBOOK ENTRIES, ETC. WHICH SHOW OR DESCRIBE INVENTION
Design of a Lunar Excavator

9. EARLIEST DATA AND PLACE INVENTION WAS CONCEIVED (Brief outline of circumstances)
1/8/85 Georgia Tech class of ME 4182

10. DATE AND PLACE OF FIRST SKETCH, DRAWING OR PHOTO
1/10/85

11. DATE AND PLACE OF FIRST WRITTEN DESCRIPTION
3/5/85 Georgia Tech

12. DISCLOSURE OF INVENTION TO OTHERS

NAME, TITLE AND ADDRESS	FORM OF DISCLOSURE	DATE AND PLACE OF DISCLOSURE	WAS SIGNATURE OBTAINED (YES OR NO)
none			

12.A IMPORTANT - HAVE ANY PUBLICATIONS OR REPORTS BEEN MADE ON THIS INVENTION?
-

13. DATE AND PLACE OF COMPLETION OF FIRST OPERATING MODEL OR FULL SIZE DEVICE
-

14. PRESENT LOCATION OF MODEL
-

15. DATE, PLACE, DESCRIPTION AND RESULTS OF FIRST TEST OR OPERATION
-

16. NAMES AND ADDRESSES OF WITNESSES OF FIRST TEST

-

17. DATE, PLACE, DESCRIPTION AND RESULTS OF LATER TESTS (name witnesses)

-

18. IDENTIFY RECORDS OF TESTS AND GIVE PRESENT LOCATION OF RECORDS

-

19. PRIOR REPORTS OR RECORDS OF INVENTION TO WHICH INVENTION IS RELATED

-

20. OTHER KNOWN CLOSELY RELATED PATENTS, PATENT APPLICATIONS AND PUBLICATIONS

PATENT OR APPLICATION NO.	DATE	TITLE OF INVENTION OR PUBLISHED ARTICLE	NAME OF PUBLICATION
-			

21. EXTENT OF USE: PAST, PRESENT AND CONTEMPLATED (Give dates, places and other pertinent details)

Possible use by 1995 for lunar construction

22. DETAILS OF INVENTION HAVE BEEN RELEASED TO THE FOLLOWING COMPANIES OR ACTIVITIES

NAME AND ADDRESS	INDIVIDUAL OR REPRESENTATIVE	CONTRACT NO.	DATE
Georgia Tech	Dr. Brazell		

SIGNATURE OF INVENTOR [illegible] DATE 3-8-85

RECORD OF INVENTION - Part II

(Attach to Record of Invention Part I)

REC. OF
INV. NO. ____________

This Disclosure of Invention should be written up in the inventor's own words and generally should follow the outline given below. Sketches, prints, photos and other illustrations as well as reports of any nature in which the invention is referred to, if available, should form a part of this disclosure and reference can be made thereto in the description of construction and operation.

1. INVENTORS NAME(S)

John Emerick, Chris Gambino, Jim Hitchcock, John Hotchkiss, Bill Rinz

2. TITLE OF INVENTION

Lunar Excavator

For answers to following questions use remainder of sheet and attach extra sheets if necessary.

3. GENERAL PURPOSE OF INVENTION. STATE IN GENERAL TERMS THE OBJECTS OF THE INVENTION.
4. DESCRIBE OLD METHOD(S) IF ANY, OF PERFORMING THE FUNCTION OF THE INVENTION.
5. INDICATE THE DISADVANTAGES OF THE OLD MEANS OR DEVICE(S).
6. DESCRIBE THE CONSTRUCTION OF YOUR INVENTION, SHOWING THE CHANGES, ADDITIONS AND IMPROVEMENTS OVER THE OLD MEANS OR DEVICES
7. GIVE DETAILS OF THE OPERATION IF NOT ALREADY DESCRIBED UNDER 6.
8. STATE THE ADVANTAGES OF YOUR INVENTION OVER WHAT HAS BEEN DONE BEFORE.
9. INDICATE ANY ALTERNATE METHODS OF CONSTRUCTION.
10. IF A JOINT INVENTION, INDICATE WHAT CONTRIBUTION WAS MADE BY EACH INVENTOR.
11. FEATURES WHICH ARE BELIEVED TO BE NEW.
12. AFTER THE DISCLOSURE IS PREPARED, IT SHOULD BE SIGNED BY THE INVENTOR(S), AND THEN READ AND SIGNED AT THE BOTTOM OF EACH PAGE BY TWO WITNESSES USING THE FOLLOWING STATEMENT:
    "DISCLOSED TO AND UNDERSTOOD BY ME THIS______DAY OF_________19___
    SIGNATURE_____________________________."

The purpose of our invention is to make an excavator for use on the moon. We know of no present excavators for this purpose. All features are believed to be new. Design of a Lunar Excavator describes our invention fully.

```
PROGRAM BACKHOE (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)

PROGRAM BACKHOE IS AN AID TO BACKHOE DESIGN.

PART I
GIVEN BACKHOE PARAMETERS SUCH AS THE BOOM LENGTH,
DIPPER STICK LENGTH, AND THEIR RANGES OF MOTION,
THIS SECTION DETERMINES THE BOOM AND DIPPER
STICK SHAPE AND THE MINIMUM AND MAXIMUM
HYDRAULIC CYLINDER LENGTHS REQUIRED.

PART II
GIVEN A MINIMUM LOAD TO BE CARRIED AT THE
DIPPER STICK-BUCKET PIN THROUGHOUT THE RANGE
OF MOTION, THIS SECTION DETERMINES THE FORCES
AT EACH PIN AND THE MINIMUM HYDRAULIC CYLINDER
BORE AREA REQUIRED FOR A GIVEN SYSTEM PRESSURE.
AFTER THE CYLINDER SIZES HAVE BEEN DETERMINED,
THE LIFT CAPACITY THROUGHOUT THE RANGE OF
MOTION IS ESTIMATED.

GIVEN THE SYSTEM HYDRAULIC FLUID FLOW
RATE, THIS SECTION DETERMINES LINK
VELOCITIES.

CURRENT PROGRAM PROGRESS:
    PART I    - COMPLETE
    PART II   - INCOMPLETE
    PART III  - INCOMPLETE

NOTES ON VECTOR NOTATION:

R - DENOTES A DISPLACEMENT VECTOR
V - DENOTES A VELOCITY VECTOR
A - DENOTES AN ACCELERATION VECTOR
T - DENOTES THE ANGLE THEYA WHICH GIVES
    THE DIRECTION OF A VECTOR
    (DIRECTION ANGLE)

EXPLANATION OF NOMENCLATURE:

MAGNITUDE
RBA - MAGNITUDE OF THE VECTOR FROM POINT A
      TO POINT B

DIRECTION
TBA - THE DIRECTION ANGLE THAT DETERMINES
      THE DIRECTION OF VECTOR RBA.  THE
      REFERENCE FROM WHICH THE DIRECTION
      ANGLES ARE MEASURED IS NOTED IN EACH
      SECTION.  ALL DIRECTION ANGLES ARE
      POSITIVE IN THE COUNTERCLOCKWISE
      DIRECTION.

KEY:
  PART I
     RBA = BOOM PIVOT LENGTH
     RBE = BOOM LENGTH
     RCB = BOOM CYLINDER LENGTH
     REG = DIPPER STICK LENGTH
     RFD = DIPPER STICK CYLINDER LENGTH

DECLARE VARIABLES:

PART I
REAL RBA, TBA, RAE, TAE, BMMAX, BMMIN, BMMS
REAL C, Z, Z1, Z2, RAC, TAC
REAL RCB, RCBMAX, RCBMIN, TCB
REAL GAMMA1, REG, TEG, DPMAX, DPMIN, DPMS
REAL RDE, TDE, RDA, TDA
REAL RFD, RFDMAX, RFDMIN, TFD
REAL RFE, TFE, GAMMA2, RGF, TGF, BETTA
REAL X, YO, Y, PSI

REAL RAD, DEG

INTEGER I, N

INITIALIZE VARIABLES:

PART I
RBA=1.0
TBA=0.0
RAE=1.0
TAE=0.0
BMMAX=0.0
BMMIN=0.0
BMMS=0.0
C=1.0
Z=1.0
Z1=1.0
Z2=1.0
RAC=1.0
TAC=0.0
RCB=1.0
RCBMAX=1.0
RCBMIN=1.0
TCB=0.0
GAMMA1=0.0
REG=1.0
TEG=0.0
DPMAX=0.0
DPMIN=0.0
DPMS=0.0
RDE=1.0
TDE=0.0
RDA=1.0
TDA=0.0
RFD=1.0
RFDMAX=1.0
RFDMIN=1.0
TFD=0.0
RFE=1.0
TFE=0.0
GAMMA2=0.0
RFG=1.0
TFG=0.0
BETTA=0.0
X=0.0
YO=1.0
Y=0.0
PSI=0.0

I=0
N=0
```

```
      PRINT*,'ANGLES ARE MEASURED FROM THE HORIZONTAL.'
      PRINT*,

      SELECT PIVOT LENGTH AND ANGLE:
      PRINT*,'ENTER PIVOT LENGTH AND ANGLE,'
      PRINT*,'BASED ON THE PIVOT DESIGN:'
      READ*, RBA, TBA
      PRINT*,
      PRINT*,'PIVOT LENGTH = ',RBA
      PRINT*,'PIVOT ANGLE = ',TBA
      PRINT*,
      PRINT*,
      TBA=RAD(TBA)

      SELECT BOOM LENGTH AND RANGE OF MOTION:
      PRINT*,'ENTER BOOM LENGTH:'
      READ*, RAE
      PRINT*,'BOOM LENGTH = ',RAE
      PRINT*,
      PRINT*,'ENTER MAXIMUM BOOM ANGLE:'
      READ*, BMMAX
      PRINT*,'MAXIMUM BOOM ANGLE = ',BMMAX
      PRINT*,
      PRINT*,'ENTER MINIMUM BOOM ANGLE:'
      READ*, BMMIN
      PRI@T*,'MINIMUM BOOM ANGLE = ',BMMIN
      PRINT*,
      PRINT*,'BOOM RANGE OF MOTION = ',ABS(BMMIN-BMMAX)
      PRINT*,
      PRINT*,
      BMMAX=RAD(BMMAX)
      BMMIN=RAD(BMMIN)

      C=(COS(TBA-BMMIN)-3.24*COS(TBA-BMMAX))/1.12

      THIS IS BASED ON THE ASSUMPTION THAT THE
      MAXIMUM HYDRAULIC CYLINDER LENGTH IS
      1.8X THE MINIMUM HYDRAULIC CYLINDER
      LENGTH.  IN THE FUTURE THIS EQUATION
      SHOULD BE DERIVED SO THAT
      MAX. LENGTH = CONSTANT X MIN. LENGTH,
      WHERE THE CONSTANT IS ASSIGNED IN A
      SUBROUTINE OR FUNCTION.

      Z1=-(RBA*C/RAE)+((RDA*C/RAE)**2-4*(RBA/RAE)**2)**0.5
      Z2=-(RBA*C/RAE)-((RDA*C/RAE)**2-4*(RBA/RAE)**2)**0.5
      Z=MAX(Z1,Z2)
      RAC=Z*RAE
      PRINT*,'BOOM CYLINDER PIN LOCATION = ',RAE
      PRINT*,
      RCBMIN=(RBA**2+RAC**2-2*RBA*RAC*COS(TBA-BMMAX))**0.5
      RCBMAX=1.8*RCBMIN

      SEE PREVIOUS COMMENT ON
      MAX. LENGTH = 1.8 X MIN. LENGTH.

      PRINT*,'BOOM CYINDER LENGTH: ',RCBMIN,' - ',RCBMAX
      PRINT*,
      PRINT*,

      PRINT*,'ANGLES ARE NOW MEASURED FROM THE '
      PRINT*,'BOTTOM OF THE BOOM.'
      PRINT*,


      SELECT DIPPER STICK LENGTH AND RANGE OF MOTION:
      PRINT*,'ENTER DIPPER STICK LENGTH:'
      READ*, REG
      PRINT*,'DIPPER STICK LENGTH = ',REG
      PRINT*,
      PRINT*,'ENTER MAXIMUM DIPPER ANGLE:'
      READ*, DPMAX
      PRINT*,'MAXIMUM DIPPER ANGLE = ',DPMAX
      PRINT*,
      PRINT*,'ENTER MINIMUM DIPPER ANGLE:'
      READ*, DPMIN
      PRINT*,'MINIMUM DIPPER ANGLE = ',DPMIN
      PRINT*,
      PRINT*,'DIPPER RANGE OF MOTION = ',ABS(DPMIN-DPMAX)
      PRINT*,
      PRINT*,
      DPMAX=RAD(DPMAX)
      DPMIN=RAD(DPMIN)

      DPMS=(DPMAX+DPMIN)/2
      TDE=DPMAX-DPMS+1.55808279

      ITERATION FOR RDA AND TDA:
      TDA=TBA-BMMAX-0.03490658
   10 RDA=RAE*(SIN(TDE)/SIN(TDE-TDA))
      IF (RDA .LT. 1.2*RBA) THEN
      TDA=TDA+0.01745329
      GO TO 10
      ELSE
      END IF
      END ITERATION

      RDE=RAE*(SIN(TDA)/SIN(TDE-TDA))

      RFDMIN=RDE*((1.0-0.88819470*SIN(TDE))/1.48)**0.5
      RFDMAX=1.8*RFDMIN

      SEE PREVIOUS COMMENT ABOUT THE ASSUMPTION
      MAX. LENGTH = 1.8 X MIN. LENGTH.

      PRINT*,'DIPPER CYLINDER LENGTH: ',RFDMIN,' - ',RFDMAX
      PRINT*,
      PRINT*,
      RFE=RDE*SIN(TDE)

      DIPPER STICK AT MAXIMUM DIPPER ANGLE:
      TFE=TDE+ACOS((RFDMIN**2-RFE**2-RDE**2)/(-2*RFE*RDE))
      BETTA=3.14159265/2.0-DPMS
      RGF=(RFE**2+REG**2-2*RFE*REG*COS(BETTA))**0.5
      TEE=TFE-ACOS((RGF**2-RFE**2-REG**2)/(2*RFE*REG))
      TGF=TFE-ACOS((REG**2-RFE**2-RGF**2)/(2*RFE*RGF))

      BOOM LINK:
      PRINT*,'BOOM SHAPE DETERMINED FROM:'
      PRINT*,
      FORMAT THIS OUTPUT
      PRINT*,'    LENGTH ',RAE,' AT ANGLE ',DEG(BMMAX)
      PRINT*,'    LENGTH ',RDA,' AT ANGLE ',DEG(TDA)
      PRINT*,'    LENGTH ',RDE,' AT ANGLE ',DEG(TDE)
      PRINT*,
      PRINT*,'ANGLES MEASURED FROM THE HORIZONTAL.'
      PRINT*,
      PRINT*,
```

```
      PRINT*, DIPPER STICK SHAPE DETERMINED FROM.
      PRINT*,
      FORMAT THIS OUTPUT (SAME AS ABOVE)
      PRINT*,'    LENGTH ',REE,' AT ANGLE ',DEG(DPMAX)
      PRINT*,'    LENGTH ',RFE,' AT ANGLE ',DEG(TFE)
      PRINT*,'    LENGTH ',RGF,' AT ANGLE ',DEG(TGF)
      PRINT*,
      PRINT*,'ANGLES MEASURED FROM THE'
      PRINT*,'BOTTOM OF THE BOOM.'
      PRINT*,
      PRINT*,
      PRINT*,'ALL ANGLES POSITIVE IN THE'
      PRINT*,'COUNTERCLOCKWISE DIRECTION.'
      PRINT*,
      PRINT*,
      PRINT*,

      POSITION ANALYSIS:

      X = DISTANCE ALONG HORIZONTAL
      X = 0 AT BOOM PIVOT

      Y = DISTANCE ALONG VERTICAL
      Y = 0 AT GROUND LEVEL
      YO = HEIGHT TO BOOM PIVOT

      PRINT*,'ENTER HEIGHT OF BOOM PIVOT:'
      READ*,YO

      DO 20 I=0,40,1
      IF (I .LT. 10) THEN
      N=I
      PSI=BMMIN+DPMIN+N*ABS(DPMIN-DPMAX)/10
      X=REA*COS(BMMIN)+REG*COS(PSI)
      Y=YO+REA*SIN(BMMIN)+REG*SIN(PSI)
      ADD FORMATED PRINT STATEMENTS.
      ELSE
      END IF

      IF (10 .LE. I .AND. I .LT. 20) THEN
      N=I-10
      PSI=BMMIN+N*ABS(BMMIN-BMMAX)/10
      X=REA*COS(PSI)+REG*COS(PSI+DPMAX)
      Y=YO+REA*SIN(PSI)+REG*SIN(PSI+DPMAX)
      ADD FORMATED PRINT STATEMENTS.
      ELSE
      END IF

      IF (20 .LE. I .AND. I .LT. 30) THEN
      N=I-20
      PSI=BMMAX+DPMIN+N*ABS(DPMIN-DPMAX)/10
      X=REA*COS(BMMAX)+REG*COS(PSI)
      Y=YO+REA*SIN(BMMAX)+REG*SIN(PSI)
      ADD FORMATED PRINT STATEMENTS.
      ELSE
      END IF

      IF (I .GE. 30) THEN
      N=I-30
      PSI=BMMAX-N*ABS(BMMIN-BMMAX)/10
      X=REA*COS(PSI)+REG*COS(PSI+DPMAX)
      Y=YO+REA*SIN(PSI)+REG*SIN(PSI+DPMAX)
      ADD FORMATED PRINT STATEMENTS.
      ELSE
      END IF

      PLACE FORMAT STATEMENTS HERE (WITHIN DO STATEMENT).

 20   CONTINUE

      STOP
      END
      FUNCTION RAD(THETA)

      FUNCTION RAD CONVERTS ANGLES IN DEGREES TO RADIANS.

      REAL THETA, RAD, PI
      PARAMETER (PI=3.14159265)

      RAD=THETA*PI/180
      END
      FUNCTION DEG(THETA)

      FUNCTION DEG CONVERTS ANGLES IN RADIANS TO DEGREES.

      REAL THETA, DEG, PI
      PARAMETER (PI=3.14159265)

      DEG=THETA*180/PI
      END
```

Cost Analysis

Constrained by time, we were unable to form a detailed cost analysis. We researched to find that an equivalent earth backhoe with roughly the same specifications would cost approximately $12,000. We broke down the costs involved in the earth backhoe into five different areas;

Area	% Total Cost	Cost
Hydraulics	25	3000
Component Manufacture	30	3600
Materials	15	1800
Assembly	30	3600
Total	100	12000

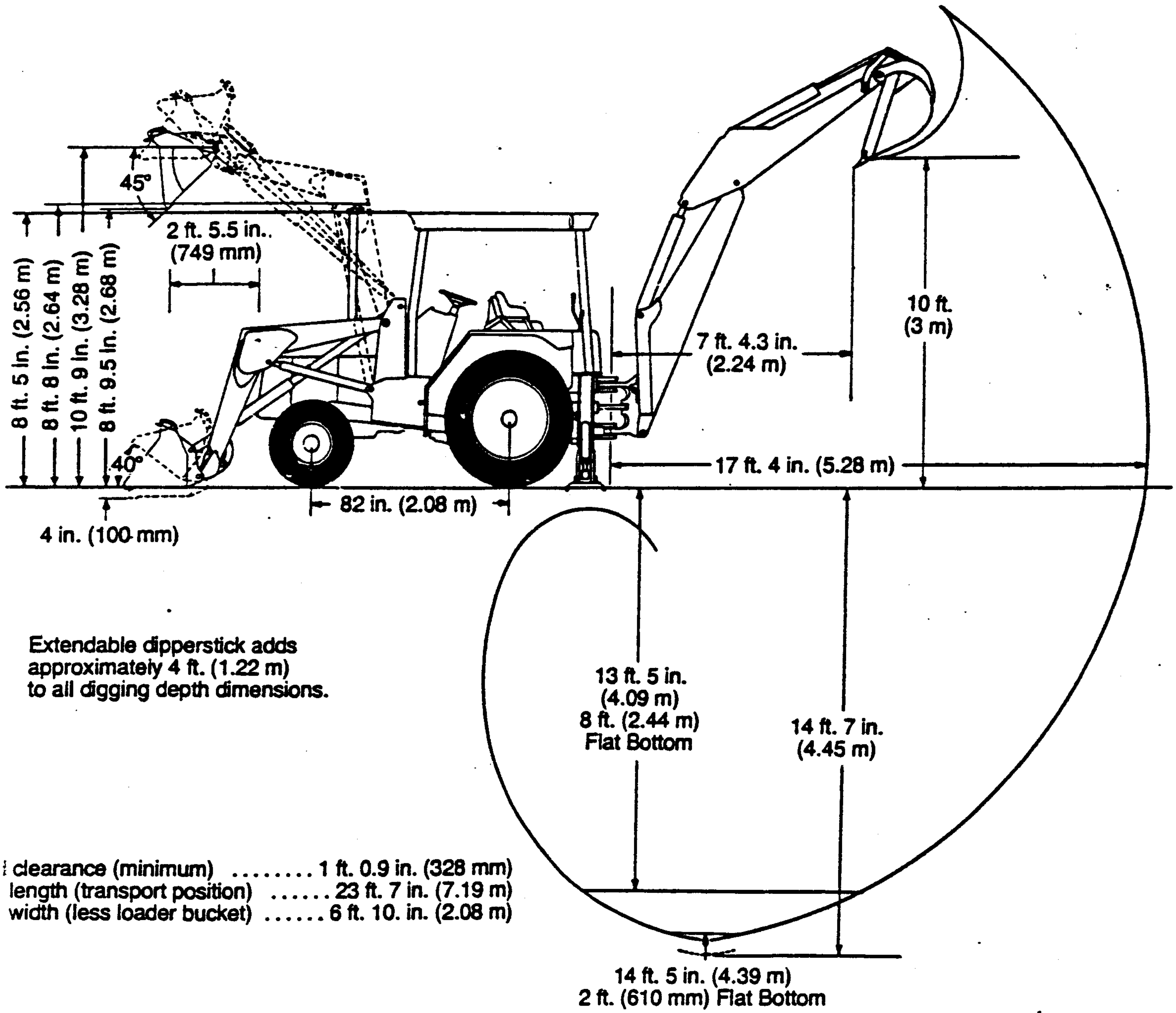
We then approximated how these areas would be affected by our design in the following areas;

Area	Old Cost	Change	New Cost
Hydraulics	3000	40%	4200
Component Manufacture	3600	150%	9000
Materials	1800	100%	3600
Assembly	3600	200%	10800
Lunar accessories	—	—	2760
Total			30,360

We arrived at a total cost of $30,360.00.

OVERHEAD PROJECTIONS

ACKHOE LOADER DIMENSIONS



Extendable dipperstick adds approximately 4 ft. (1.22 m) to all digging depth dimensions.

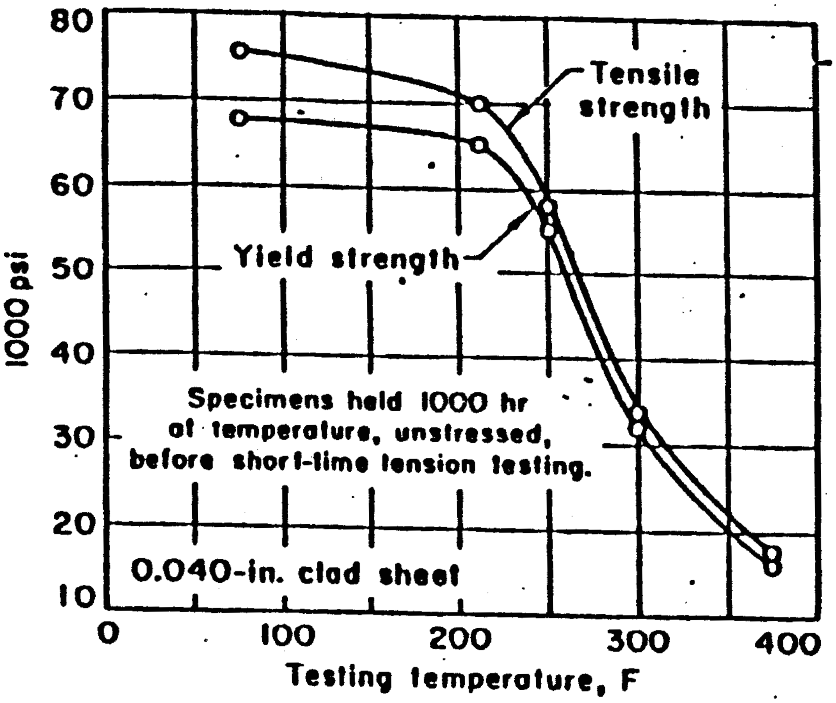
clearance (minimum)	1 ft. 0.9 in. (328 mm)
length (transport position)	23 ft. 7 in. (7.19 m)
width (less loader bucket)	6 ft. 10. in. (2.08 m)

Decision Matrix for Materials

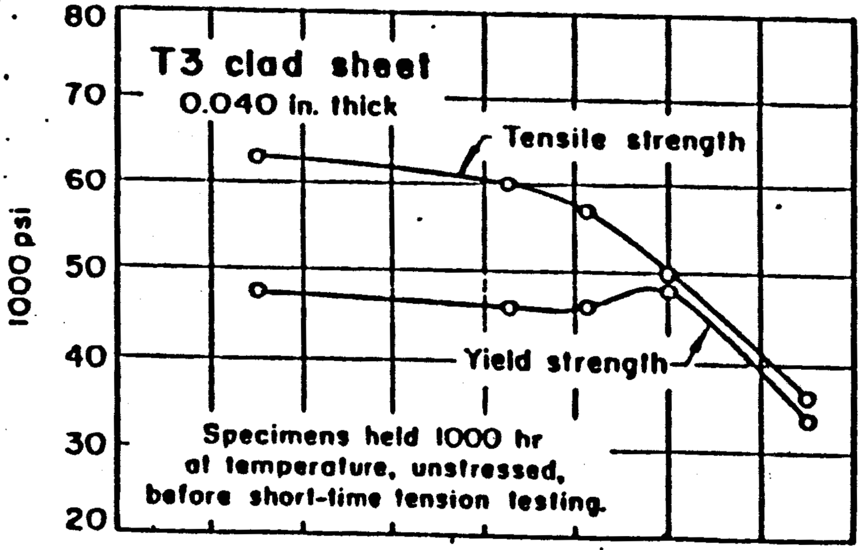
	Amount of Information	Low Temp. Properties	High Temp. Properties	Strength-to-Weight Ratio	Ductility	Cost	Manufacturability	Total
Al Alloys	10	10	7	8	10	10	10	65
Ti Alloys	10	4	9	9	6	3	10	51
Al-Li Alloys	2	7	8	9	10	2	10	48
Graphite Reinforced Composites	3	9	8	10	8	1	8	47
Ceramics	9	4	8	6	2	7	2	38
Low Carbon Steels	10	1	10	6	8	10	10	55
Low Carbon Ni-Steels	8	10	10	6	8	10	10	62
Mg Alloys	10	4	9	7	8	6	4	48

From the matrix, it is apparent that Al Alloys and Low Carbon Ni-Steels should be looked at more carefully.

Al-7075



Al-2024



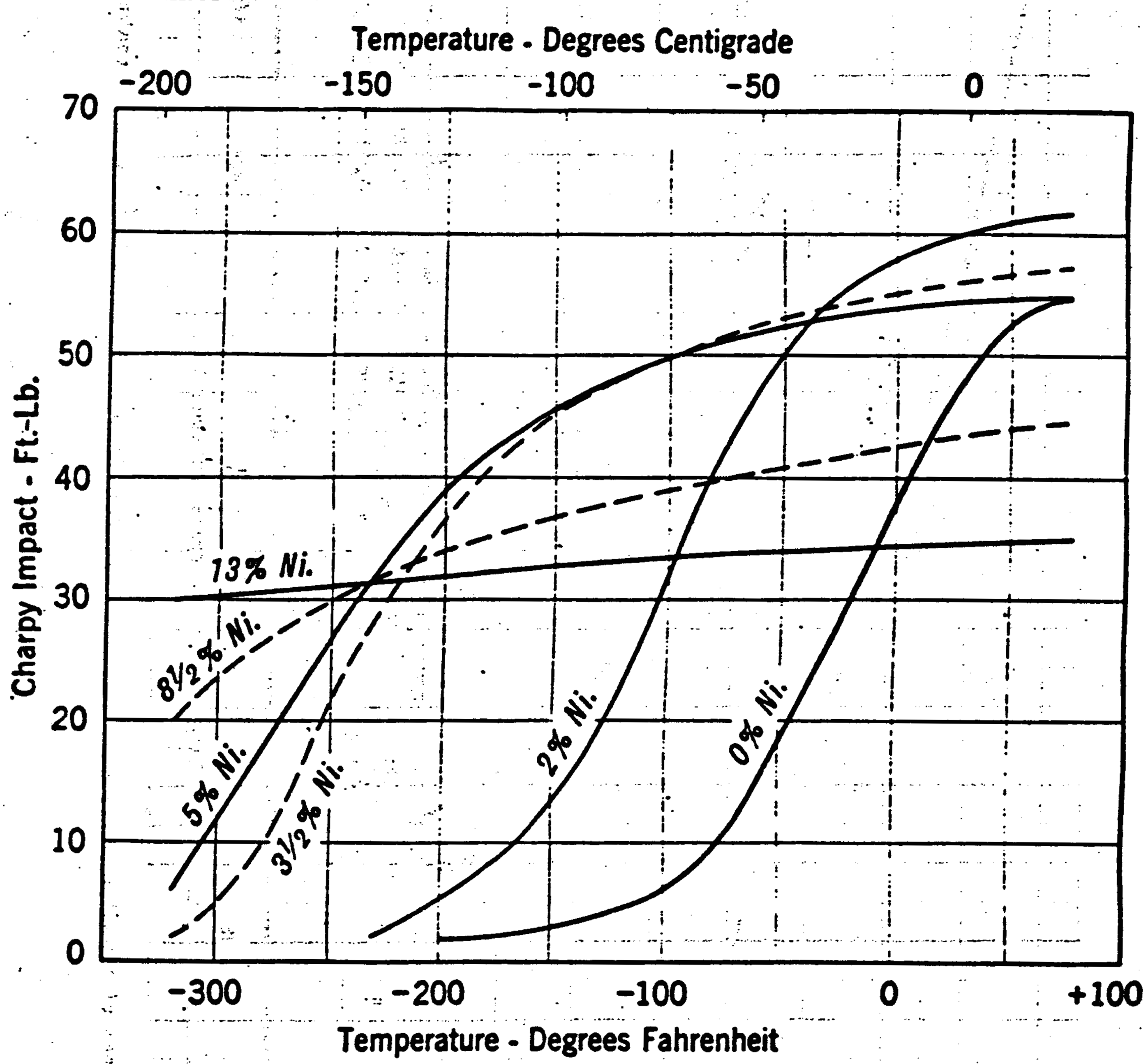
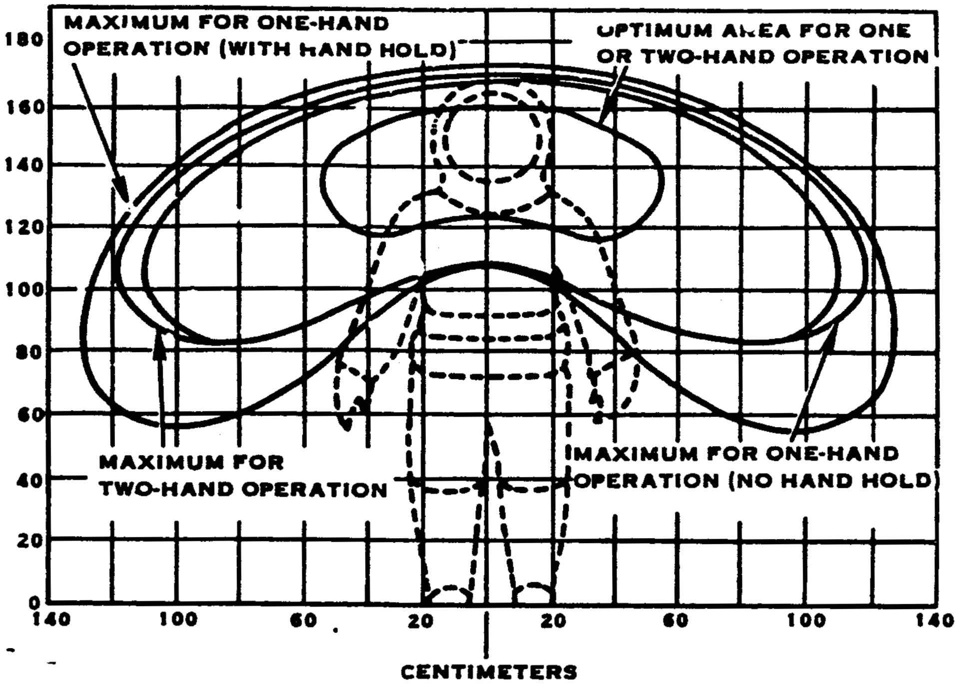


Figure 23. Effect of nickel content on the resistance to low-temperature embrittlement of normalized low-carbon steels. (Keyhole notch.) All steels contain 0.10% carbon except No. 1020 (0.20%) and the 2% nickel steel (0.15%).



EVA CREWMAN SIDE REACH ENVELOPE

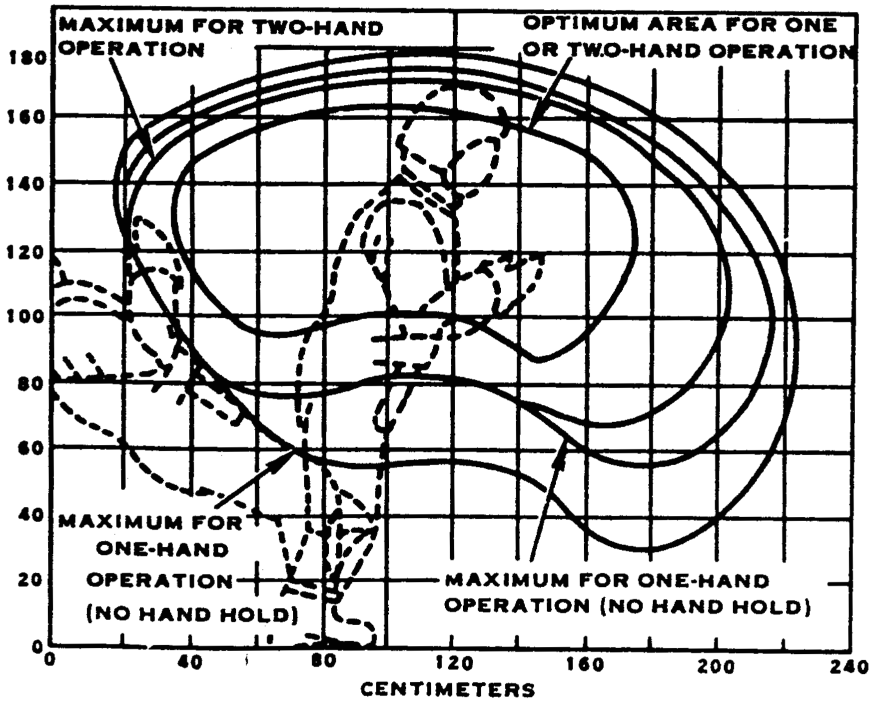
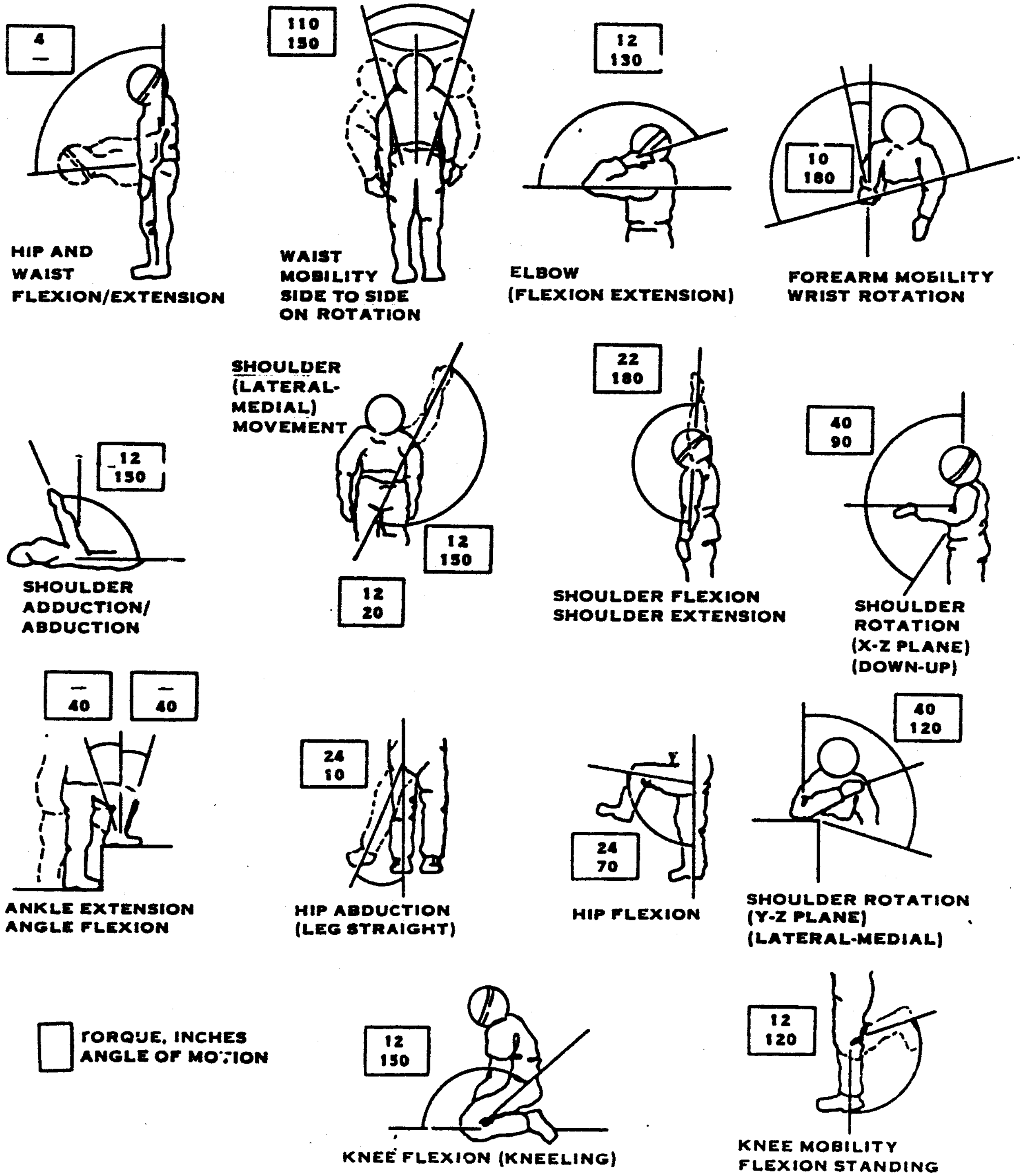


FIGURE 12. EVA CREWMAN FORE-AFT REACH ENVELOPE

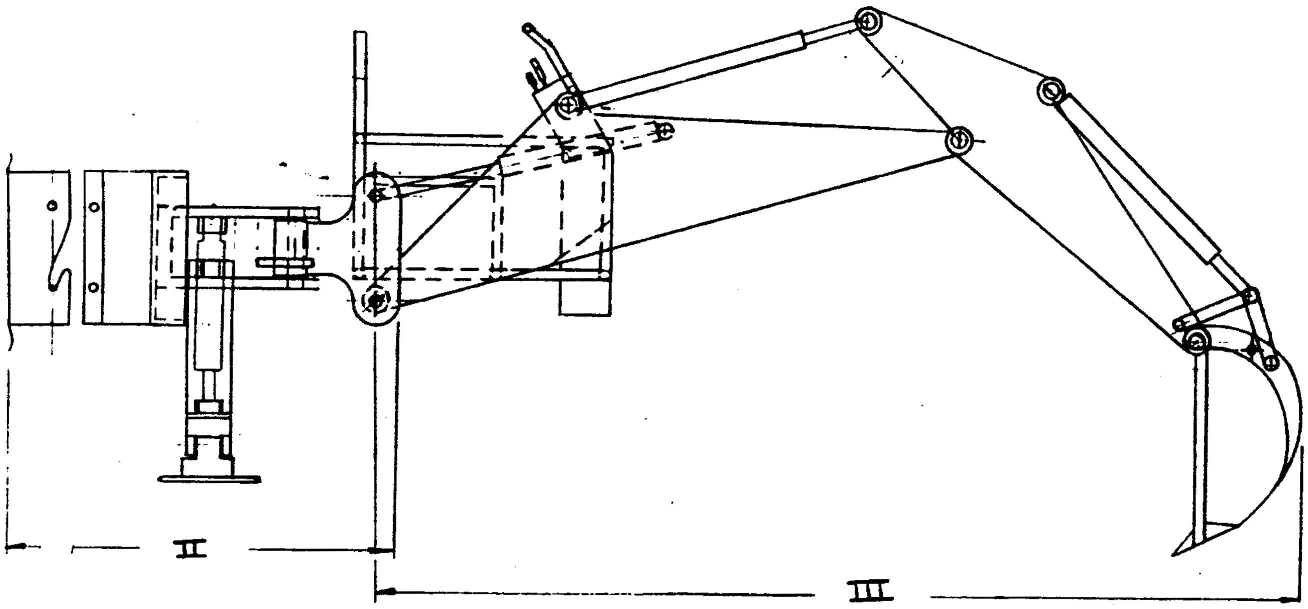
UNITED TECHNOLOGIES
HAMILTON STANDARD

TABLE II. MOBILITY REQUIREMENTS (AT 4.0 ± 0.20 PSIG) (CONTINUED)



II. INTERF

III. ARM



LUNAR BACKHOE IMPLEME

SCALE: 1:20

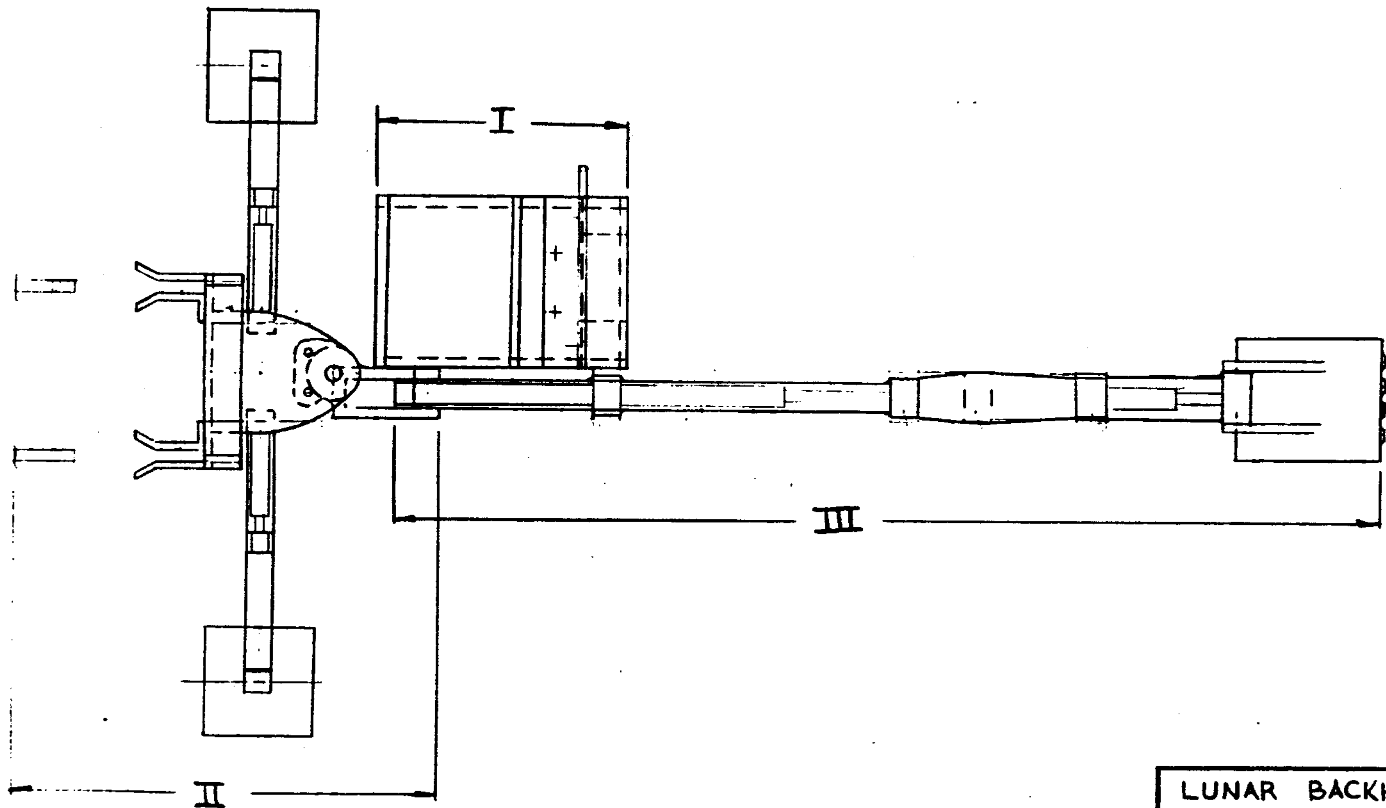
DATE: 12 MAR 85

APPROVED BY: C. GAMBINO

ASSEMBLY DRAWING, SI

ME 4182 TU-5:30

I. OF
II. IN
III. A



LUNAR BACKHOE	
SCALE: 1:20	APPROVED BY: C. GA
DATE: 12 MAR 85	
ASSEMBLY DRAWI	
ME 4182	TU: 5:

Group 10
CONTROL VALVE ASSEMBLY

GENERAL INFORMATION

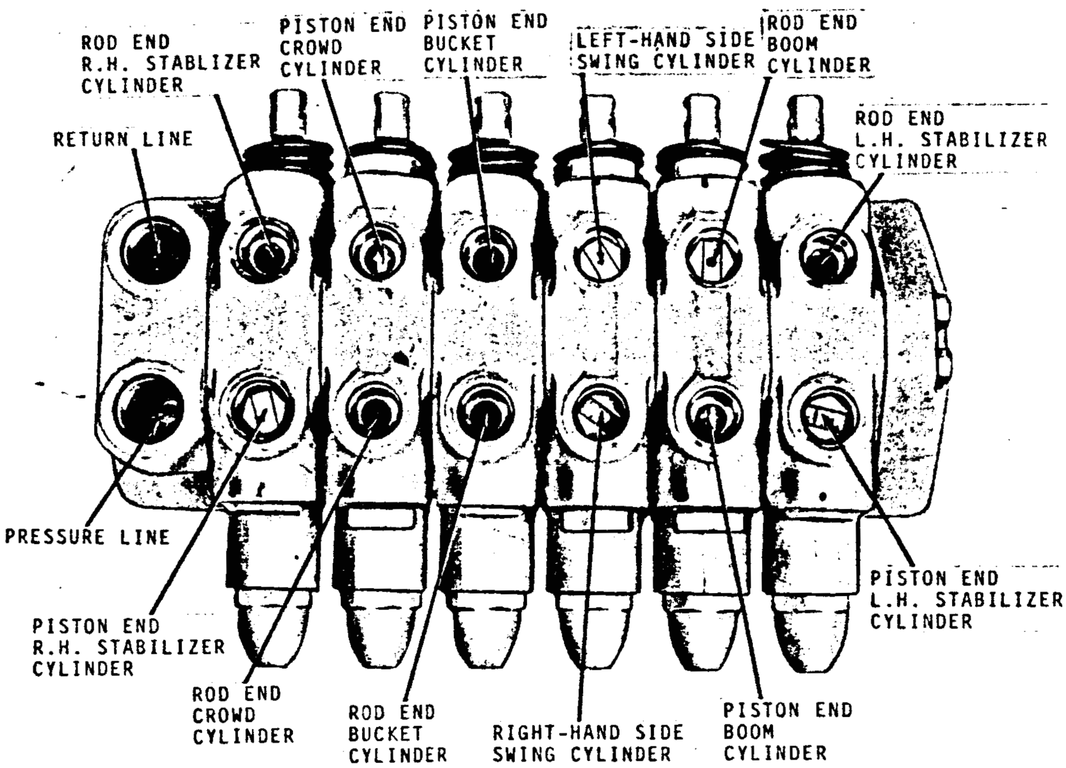


Fig. 1-Identifying Control Valve Parts (9250 shown)

The closed-center control valve (Fig. 1) is an assembly of six individual double-acting valves with a plate on each end of the stack assembly. All hydraulic action of the backhoe is controlled by the valves, with each valve controlling oil flow to and from one cylinder. Refer to Fig. 2 for oil flow through the valve.

Relief valves are used in the crowd, boom, and swing valve to protect these circuits from excessive pressure.

As shown in Fig. 2, the oil flow through the closed-center control valve is blocked by the end plate. When a control lever is moved, oil under pressure is directed to one of the working cylinders, through the cylinder, back to the control valve, out the port plate and back to the auxiliary return oil filter.

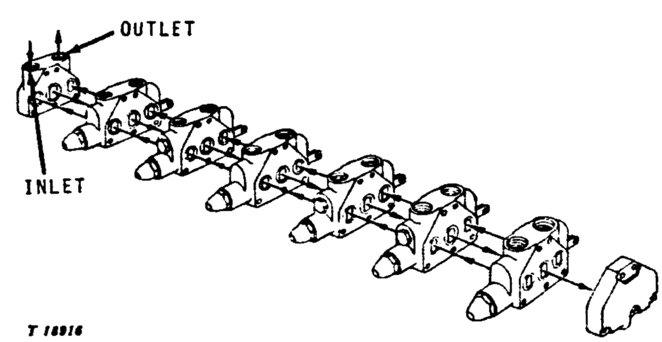


Fig. 2-Oil Flow in Control Valve

Oil flow through the swing valve section is shown in Figs. 3 and 4.

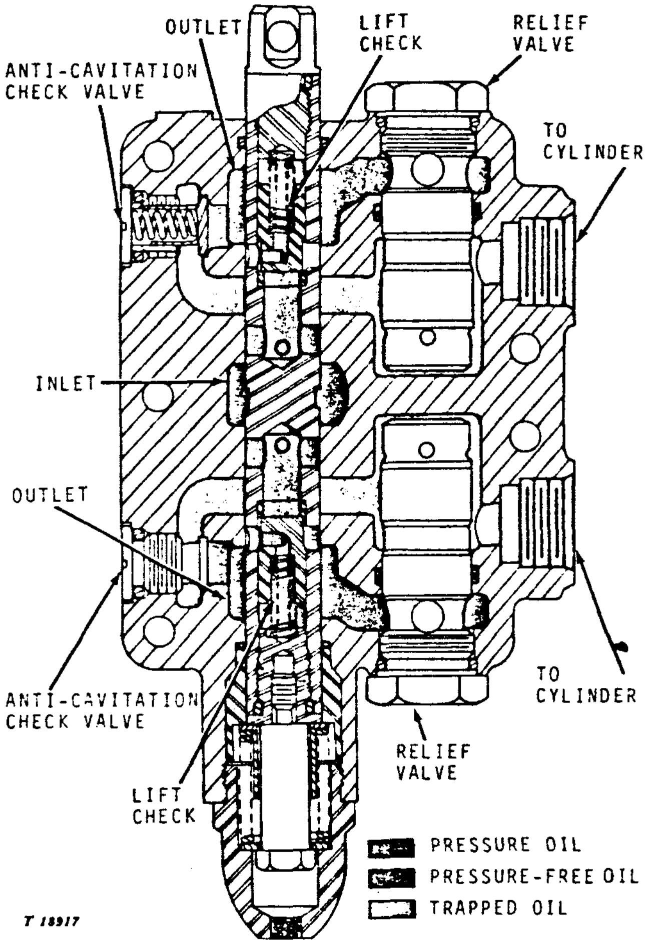


Fig. 3-Swing Valve in Neutral Position

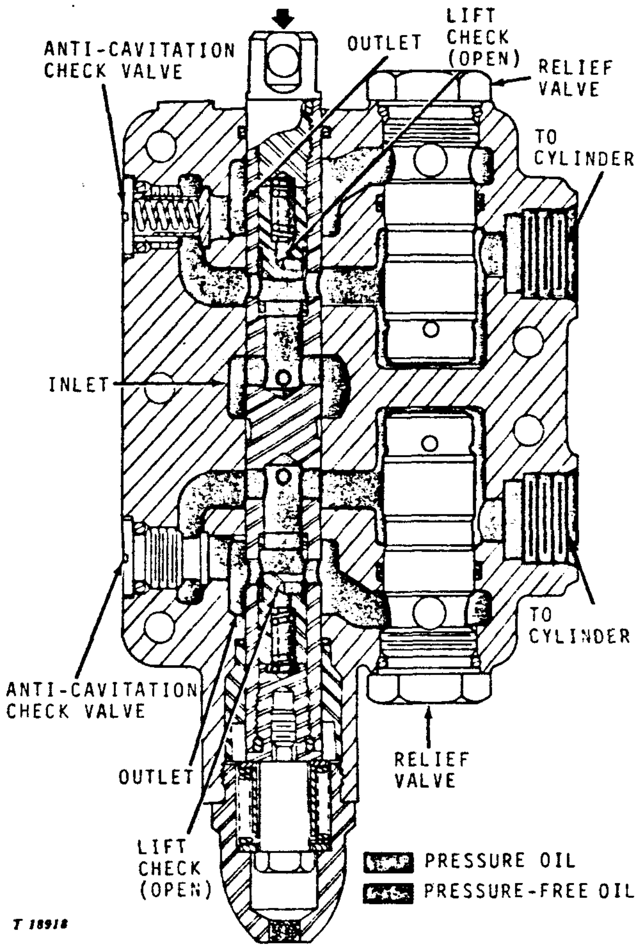


Fig. 4-Swing Valve in Power Position

In the neutral position (Fig. 3), the spool blocks oil flow to both ports. Any pressure oil leakage past the spool is collected in the bleed-off grooves in the spool.

As this leakage oil pressure builds, the load lift checks in the spool open, allowing the leakage oil to return to the reservoir. This prevents the leakage oil from entering the port passages and causing the cylinder rod to extend.

In the power position (Fig. 4), the pressure oil enters the bore of the spool, unseats the load lift check, and flows through the port to the cylinder.

Return oil from the cylinder enters the bore of the spool, unseats the load lift check, and returns through the outlet passage to the reservoir.

DIAGNOSIS AND TEST

Refer to Group 5, "Diagnosing Malfunctions" for isolating component failures.

Test the valves for leaks as follows:

Raise the loaded bucket a few feet off the ground and shut off the engine.

Disconnect the dump line leading from the control valve to the reservoir.

If the load settles and oil is leaking past the valve spools, oil will leak from the disconnected oil line.

Reconnect the oil line and lower the bucket to the ground.

If the check valves appear to be leaking, check as follows:

Start the engine. Raise the loaded bucket a few feet off the ground, and return the control valve to neutral.

Slowly move the control lever back to the raise position. If the load settles before it begins to rise, the check valve is probably leaking. Repeat the check with the bucket control.

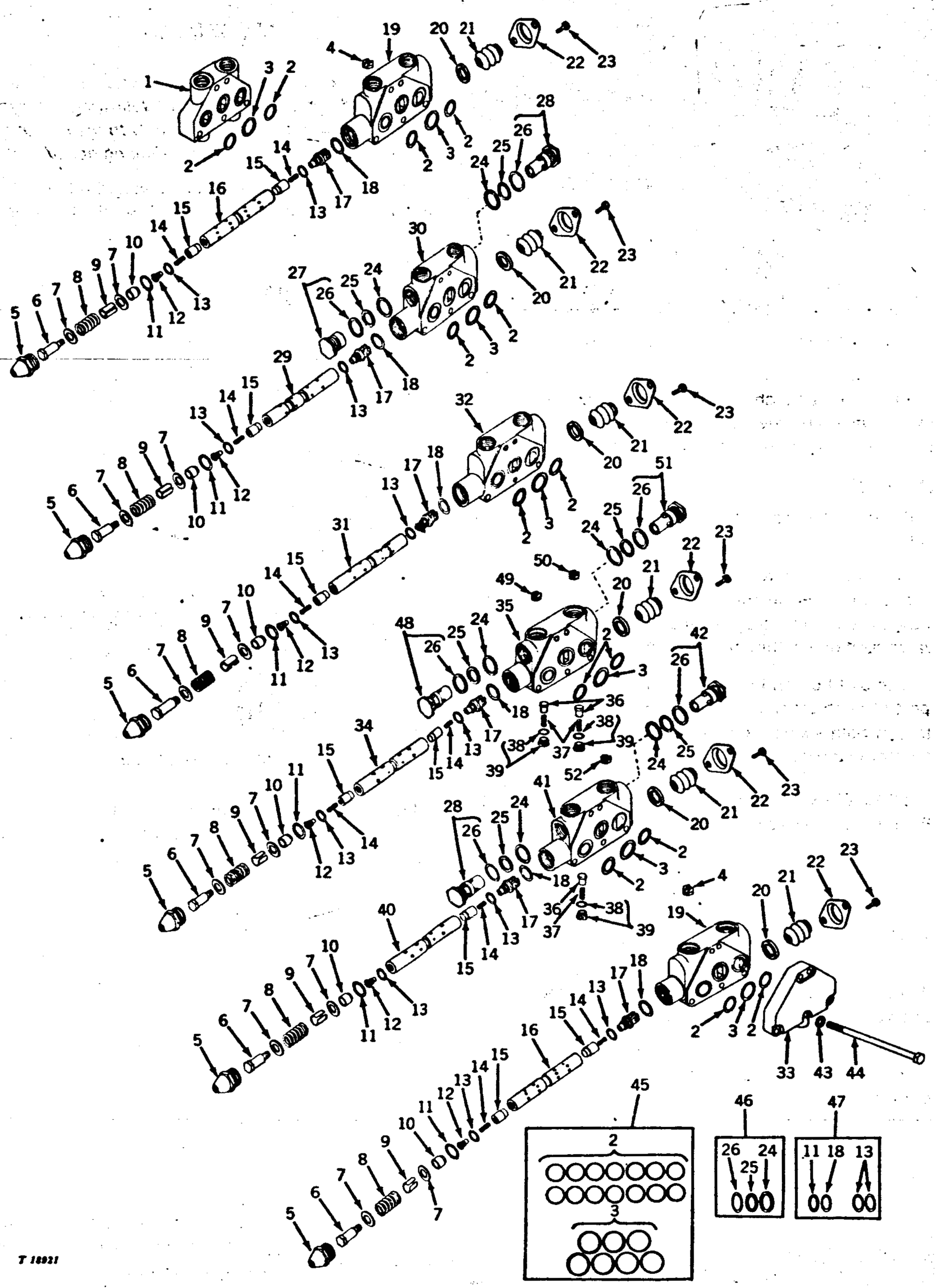


Fig. 13-Exploded View of Control Valve

REC. OF
INV. NO. ________________

INVENTOR ____ 19____

DISCLOSED TO AND UNDERSTOOD BY ME
THIS 8 DAY OF March 19 85
L.B Gabis
WITNESS

DISCLOSED TO AND UNDERSTOOD BY ME
ON THIS 8 DAY OF March 19 85
WITNESS

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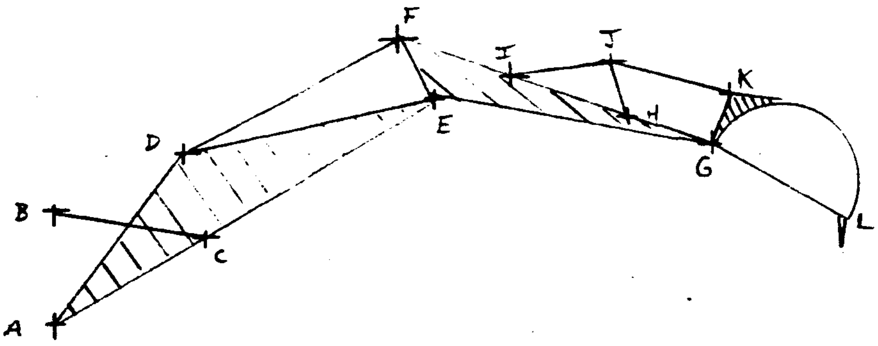
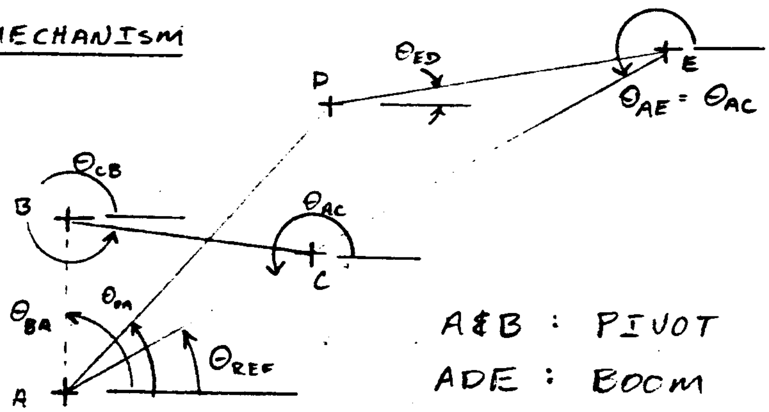
BACKHOE



BOOM MECHANISM



A&B : PIVOT INTERFACE

ADE : BOOM

BC : BOOM CYLINDER

Loop Closure:

$$\bar{R}_{BA} + \bar{R}_{CB} + \bar{R}_{AC} = 0$$

$$R_{BA}\, e^{j\theta_{BA}} + R_{CB}\, e^{j\theta_{CB}} + R_{AC}\, e^{j\theta_{AC}} = 0$$

$$e^{j\theta} = \cos\theta + j\sin\theta :$$

$$R_{BA}(\cos\theta_{BA} + j\sin\theta_{BA}) + R_{CB}(\cos\theta_{CB} + j\sin\theta_{CB}) + R_{AC}(\cos\theta_{AC} + j\sin\theta_{AC}) = 0$$

which, when broken into real & imaginary parts, becomes

$$R_{BA}\cos\theta_{BA} + R_{CB}\cos\theta_{CB} + R_{AC}\cos\theta_{AC} = 0$$

$$R_{BA}\sin\theta_{BA} + R_{CB}\sin\theta_{CB} + R_{AC}\sin\theta_{AC} = 0$$

PIVOT INTERFACE

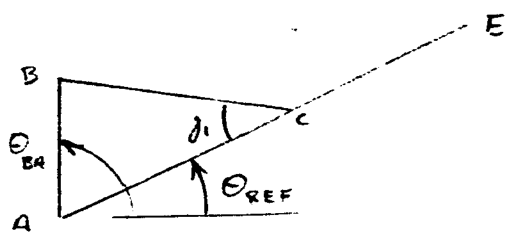
- Select R_{BA} and θ_{BA} based on the Pivot design. θ_{BA} usually equals 70°.

Boom :

- Select Boom Length, R_{AE}
- Select Boom Range of Motion ($\theta_{REF_{MAX}}$ & $\theta_{REF_{MIN}}$)

$\angle 65°$ $\angle -80°$

Let $R_{AC} = x R_{AE}$, where $0 < x < 1$



Note: Make this section optional so that computer or designer may select location of C. Use prompt & conditional.

Let $R_{CB_{MAX}} \approx 1.8\, R_{CB_{MIN}}$

$$R_{CB}^2 = R_{BA}^2 + R_{AC}^2 - 2 R_{BA} R_{AC} \cos(\theta_{BA} - \theta_{REF})$$

$$\therefore \quad R_{CB_{MIN}}^2 = R_{BA}^2 + (x R_{AE})^2 - 2 R_{BA}\, x R_{AE} \cos(\theta_{BA} - \theta_{REF_{MAX}})$$

$$R_{CB_{MAX}} = (1.8)^2 R_{CB_{MIN}}^2 = R_{BA}^2 + (x R_{AE})^2 - 2 R_{BA}\, x R_{AE} \cos(\theta_{BA} - \theta_{REF_{MIN}})$$

solve simultaneously :

$$3.24\, R_{CB_{MIN}}^2 = R_{BA}^2 + (x R_{AE})^2 - 2 R_{BA} x R_{AE} \cos(\theta_{BA} - \theta_{REF_{MIN}})$$

$$R_{CB_{MIN}}^2 = R_{BA}^2 + (x R_{AE})^2 - 2 R_{BA} x R_{AE} \cos(\theta_{BA} - \theta_{REF_{MAX}})$$

$$3.24\, R_{CB_{MIN}}^2 = 3.24\, R_{BA}^2 + 3.24 (x R_{AE})^2 - 6.48\, R_{BA} x R_{AE} \cos(\theta_{BA} - \theta_{REF_{MAX}}$$

$$3.24\, R_{CB_{MIN}}^2 = R_{BA}^2 + (x R_{AE})^2 - 2 R_{BA} x R_{AE} \cos(\theta_{BA} - \theta_{REF_{MIN}}$$

$$\begin{aligned} 0 &= 2.24\, R_{BA}^2 + 2.24 (x R_{AE})^2 \\ &\quad - 6.48\, R_{BA}\, x\, R_{AE} \cos(\theta_{BA} - \theta_{REF_{MAX}}) \\ &\quad + 2 R_{BA}\, x\, R_{AE} \cos(\theta_{BA} - \theta_{REF_{MIN}}) \end{aligned}$$

$$\begin{aligned} &= 1.12\, R_{BA}^2 + 1.12 (x R_{AE})^2 \\ &\quad + R_{BA}\, x\, R_{AE} [\cos(\theta_{BA} - \theta_{REF_{MIN}}) - 3.24 \cos(\theta_{BA} - \theta_{REF_{MAX}}) \end{aligned}$$

let $$K_1 = \frac{\cos(\theta_{BA} - \theta_{REF,MIN}) - 3.24 \cos(\theta_{BA} - \theta_{REF,MAX})}{1.12}$$

so that

$$0 = R_{BA}^2 + x^2 R_{AE}^2 + R_{BA} R_{AE} K_1 x$$

$$R_{AE}^2 x^2 + R_{BA} R_{AE} K_1 x + R_{BA}^2 = 0$$

$$x^2 + \frac{R_{BA} K_1}{R_{AE}} x + \left(\frac{R_{BA}}{R_{AE}}\right)^2 = 0$$

$$x = \frac{-\left(\frac{R_{BA} K}{R_{AE}}\right) \pm \sqrt{\left(\frac{R_{BA} K_1}{R_{AE}}\right)^2 - 4\left(\frac{R_{BA}}{R_{AE}}\right)^2}}{2}$$

and $$R_{AC} = x R_{AE}$$

$$R_{CB_{MIN}} = [R_{BA}^2 + R_{AC}^2 - 2 R_{BA} R_{AC} \cos(\theta_{BA} - \theta_{REF_{MAX}})]$$

Example: $R_{BA} = 1$ ft $\quad \theta_{REF_{MAX}} = 65°$

$R_{AE} = 5$ ft $\quad \theta_{REF_{MIN}} = -80°$

$\theta_{BA} = 90°$

$$K_1 = \frac{\cos(\theta_{BA} - \theta_{REF,MIN}) - 3.24\cos(\theta_{BA} - \theta_{REF,MAX})}{1.12}$$

$$= \frac{\cos(90° + 80°) - 3.24\cos(90° - 65°)}{1.12}$$

$$= -3.5011$$

$$x = \frac{-\left(\frac{R_{BA}K}{R_{AE}}\right) \pm \sqrt{\left(\frac{R_{BA}K}{R_{AE}}\right)^2 - 4\left(\frac{R_{BA}}{R_{AE}}\right)^2}}{2}$$

$$\left(\frac{R_{BA}K}{R_{AE}}\right) = \frac{(1)(-3.5011)}{5} = -0.7002$$

$$\left(\frac{R_{BA}K}{R_{AE}}\right)^2 = 0.4903$$

$$\left(\frac{R_{BA}}{R_{AE}}\right)^2 = \left(\frac{1}{5}\right)^2 = 0.04$$

$$= \left(0.7002 \pm \sqrt{0.4903 - 4(0.04)}\right)/2$$

$$= (0.7002 \pm 0.5747)/2$$

$$= 0.6375, \quad 0.0628$$ choose $x = 0.6375$

$$R_{AC} = (0.6375)(5) = 3.19 \text{ ft}$$

$$R_{CB_{MIN}} = \left[1^2 + 3.19^2 - 2(1)(3.19)\cos(90° - 65°)\right]^{1/2}$$

$$= 2.32 \text{ ft}$$

$$R_{BA}^2 = R_{CB}^2 + R_{AC}^2 - 2 R_{CB} R_{AC} \cos\gamma_1$$

$$\cos\gamma_1 = \frac{R_{CB}^2 + R_{AC}^2 - R_{BA}^2}{2 R_{CB} R_{AC}}$$

$$\gamma_1 = \cos^{-1}\left(\frac{R_{CB}^2 + R_{AC}^2 - R_{BA}^2}{2 R_{CB} R_{AC}}\right)$$

$\gamma_{1\,RETRACTED}$ when $R_{CB} = R_{CB\,MIN}$

so far,
- Select R_{BA} and θ_{BA} base on the pivot interface design.
- Select R_{AE}
- Select θ_{REF} min & max
- Computer Determines
  - R_{AC} – The location on the boom where the boom cylinder connects to the boom
  - $R_{CB_{MIN}}$ – the minimum length of the boom cylinder

$$\gamma_{1\,RETRACTED} = \cos^{-1}\left(\frac{R_{CB_{MIN}}^2 + R_{AC}^2 - R_{BA}^2}{2 R_{CB_{MIN}} R_{AC}}\right)$$

Loop Closure:

$$R_{BA} \cos\theta_{BA} + R_{CB} \cos\theta_{CB} + R_{AC} \cos\theta_{AC} = 0$$

$$R_{BA} \sin\theta_{BA} + R_{CB} \sin\theta_{CB} + R_{AC} \sin\theta_{AC} = 0$$

R_{BA} ✓ $\quad \theta_{BA}$ ✓

R_{CB} ✓ $1.0\,R_{CB\,MIN}$ / $1.5\,R_{CB\,MIN}$ $\quad \theta_{CB}$

R_{AC} ✓ $\quad \theta_{AC}$

$\Big\}$ solve above simultaneously for θ_{CB} & θ_{AC} given R_{CB}.

Isolate θ_{AC} terms:

$$-R_{AC}\cos\theta_{AC} = R_{BA}\cos\theta_{BA} + R_{CB}\cos\theta_{CB}$$
$$-R_{AC}\sin\theta_{AC} = R_{BA}\sin\theta_{BA} + R_{CB}\sin\theta_{CB}$$

Square both sides of these equations:

$$R_{AC}^2\cos^2\theta_{AC} = R_{BA}^2\cos^2\theta_{BA} + R_{CB}^2\cos^2\theta_{CB} + 2R_{BA}\cos\theta_{BA}R_{CB}\cos\theta_{CB}$$
$$R_{AC}^2\sin^2\theta_{AC} = R_{BA}^2\sin^2\theta_{BA} + R_{CB}^2\sin^2\theta_{CB} + 2R_{BA}\sin\theta_{BA}R_{CB}\sin\theta_{CB}$$

Add the two equations together:

$$R_{AC}^2 = R_{BA}^2 + R_{CB}^2 + 2R_{BA}R_{CB}(\cos\theta_{BA}\cos\theta_{CB} + \sin\theta_{BA}\sin\theta_{CB})$$

$$\cos(\alpha-\beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta$$

$$R_{AC}^2 = R_{BA}^2 + R_{CB}^2 + 2R_{BA}R_{CB}\cos(\theta_{BA}-\theta_{CB})$$

$$\cos(\theta_{BA}-\theta_{CB}) = \frac{R_{AC}^2 - R_{BA}^2 - R_{CB}^2}{2R_{BA}R_{CB}}$$

$$\theta_{BA}-\theta_{CB} = \cos^{-1}\left(\frac{R_{AC}^2 - R_{BA}^2 - R_{CB}^2}{2R_{BA}R_{CB}}\right)$$

$$\theta_{CB} = \theta_{BA} - \cos^{-1}\left(\frac{R_{AC}^2 - R_{BA}^2 - R_{CB}^2}{2R_{BA}R_{CB}}\right)$$

Isolate θ_{CB} terms:

$$-R_{CB}\cos\theta_{CB} = R_{BA}\cos\theta_{BA} + R_{AC}\cos\theta_{AC}$$
$$-R_{CB}\sin\theta_{CB} = R_{BA}\sin\theta_{BA} + R_{AC}\sin\theta_{AC}$$

Square both sides of these equations:

$$R_{CB}^2\cos^2\theta_{CB} = R_{BA}^2\cos^2\theta_{BA} + R_{AC}^2\cos^2\theta_{AC} + 2R_{BA}\cos\theta_{BA}\,R_{AC}\cos\theta_{AC}$$
$$R_{CB}^2\sin^2\theta_{CB} = R_{BA}^2\sin^2\theta_{BA} + R_{AC}^2\sin^2\theta_{AC} + 2R_{BA}\sin\theta_{BA}\,R_{AC}\sin\theta_{AC}$$

Add the two equations together:

$$R_{CB}^2 = R_{BA}^2 + R_{AC}^2 + 2R_{BA}R_{AC}\left(\cos\theta_{BA}\cos\theta_{AC} + \sin\theta_{BA}\sin\theta_{AC}\right)$$

$$R_{CB}^2 = R_{BA}^2 + R_{AC}^2 + 2R_{BA}R_{AC}\cos\left(\theta_{BA} - \theta_{AC}\right)$$

$$\theta_{BA} - \theta_{AC} = \cos^{-1}\left(\frac{R_{CB}^2 - R_{BA}^2 - R_{AC}^2}{2R_{BA}R_{AC}}\right)$$

$$\theta_{AC} = \theta_{BA} - \cos^{-1}\left(\frac{R_{CB}^2 - R_{BA}^2 - R_{AC}^2}{2R_{BA}R_{AC}}\right)$$

Program, so far:

- Select R_{BA} and θ_{BA} base on the pivot design. θ_{BA} usually equals $90°$
- Select Boom Length, R_{AE}.
- Select Boom Range of Motion, θ_{REF} Max & Min
- Computer Determines R_{AC}:

$$K_1 = \frac{\cos(\theta_{BA} - \theta_{REF,MIN}) - 3.24\cos(\theta_{BA} - \theta_{REF,MAX})}{1.12}$$

NEED BETTER ESTIMATE

based on the assumtion $R_{CB,max} = 1.8 R_{CB,m}$

$$x = MAX\left(\frac{-\left(\frac{R_{BA}K}{R_{AE}}\right) \pm \sqrt{\left(\frac{R_{BA}K}{R_{AE}}\right)^2 - 4\left(\frac{R_{BA}}{R_{AE}}\right)^2}}{2} \right)$$

$$R_{AC} = x R_{AE}$$

- Computer Determines $R_{CB_{MIN}}$

$$R_{CB,MIN} = \left[R_{BA}^2 + R_{AC}^2 - 2R_{BA}R_{AC}\cos(\theta_{BA} - \theta_{REF_{max}})\right]$$

- Allow R_{CB} to vary:

R_{BA}, R_{AC}, θ_{BA} = constant

R_{CB} given

$$\theta_{CB} = \theta_{BA} - \cos^{-1}\left(\frac{R_{AC}^2 - R_{BA}^2 - R_{CB}^2}{2R_{BA}R_{CB}}\right)$$

$$\theta_{AC} = \theta_{BA} - \cos^{-1}\left(\frac{R_{CB}^2 - R_{BA}^2 - R_{AC}^2}{2R_{BA}R_{CB}}\right)$$

θ_{ι} ...

$$\theta_{REF} = \theta_{AC} - 180^\circ$$

$$\gamma_1 = \cos^{-1}\left(\frac{R_{CB}^2 + R_{AC}^2 - R_{BA}^2}{2 R_{CB} R_{AC}} \right)$$

Constraints:

$R_{DA} > R_{BA}$

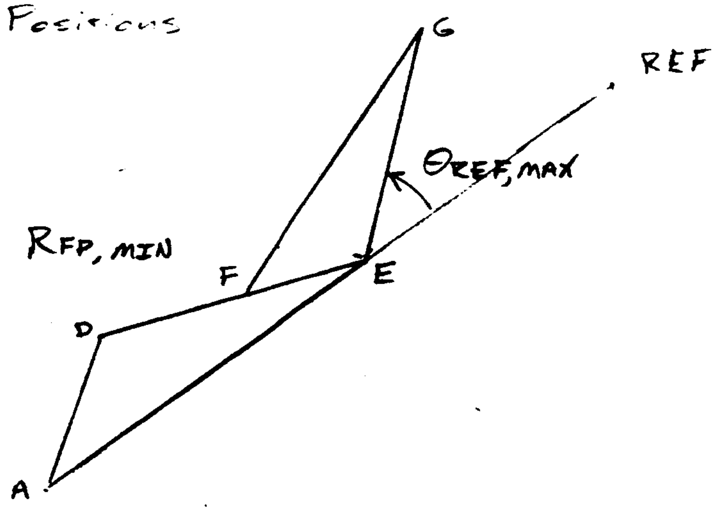
$\theta_{DA} \leq \theta_{BA}$ at $\theta_{REF,max}$

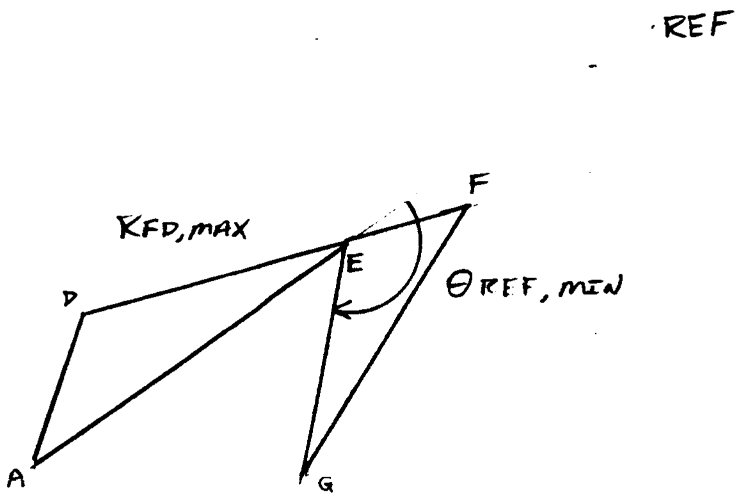
So that there is no interference between the pivot and the boom.

DIPPER STICK

All angles now measured wrt R_{AE}

Extreme Positions



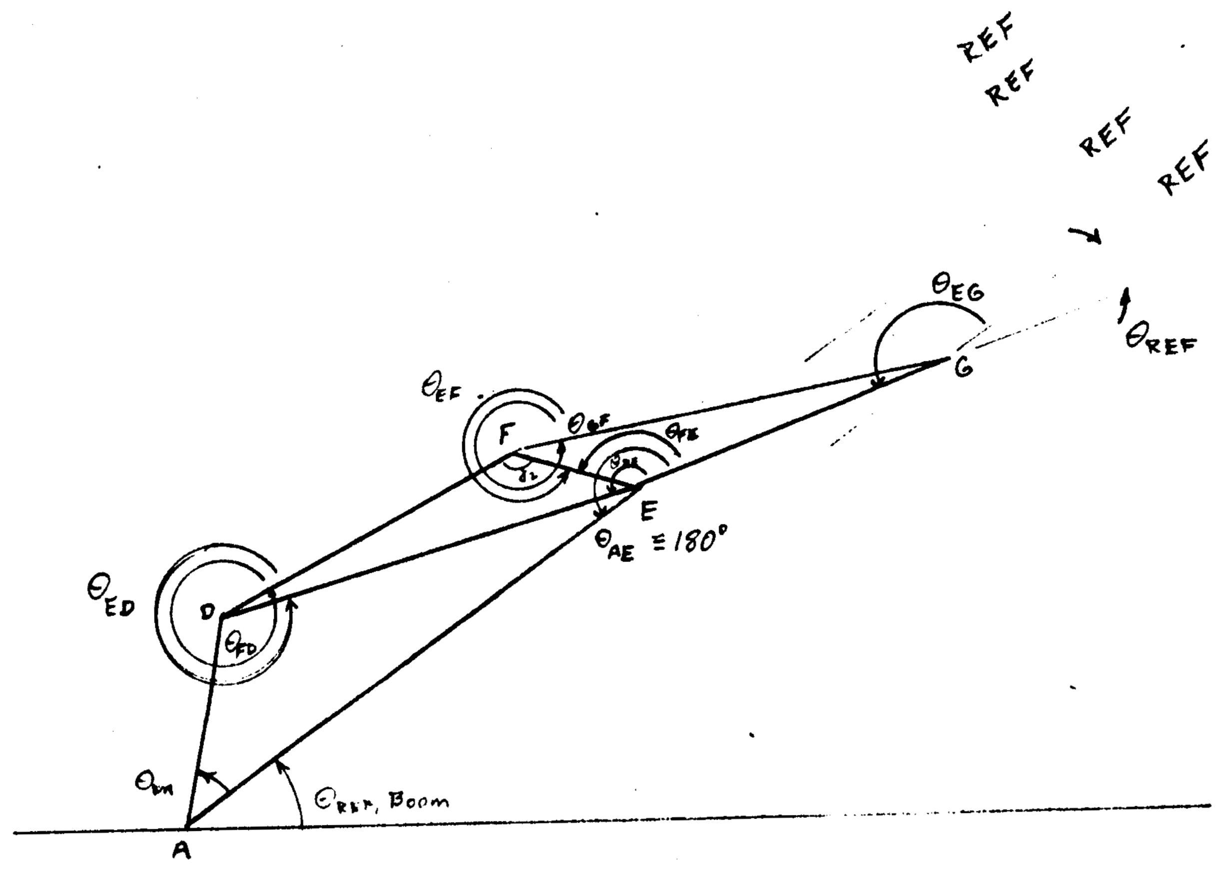


D & E : BOOM INTERFACE

ADE : BOOM

EFG : DIPPER STICK

DF : DIPPER STICK CYLINDER



REF
REF
REF
REF
θ_{EG}
θ_{REF}
G
θ_{EF}
F
E
$\theta_{AE} = 180°$
θ_{ED}
D
θ_{FD}
A
θ_{REF}, Boom

- Select Dipper Stick Length, R_{EG}
- Select Dipper Stick Range of Motion ($\theta_{REF,MAX}$ & $\theta_{REF,MIN}$)

$\angle 0°$ $\angle -110°$

Loop Closure Equations:

1. ADE Loop (Boom Link)

$$R_{DA}\, e^{j\theta_{DA}} + R_{ED}\, e^{j\theta_{ED}} + R_{AE}\, e^{j\theta_{AE}} = 0$$

2. DFE Loop

$$R_{FD}\, e^{j\theta_{FD}} + R_{EF}\, e^{j\theta_{EF}} + R_{DE}\, e^{j\theta_{DE}} = 0$$

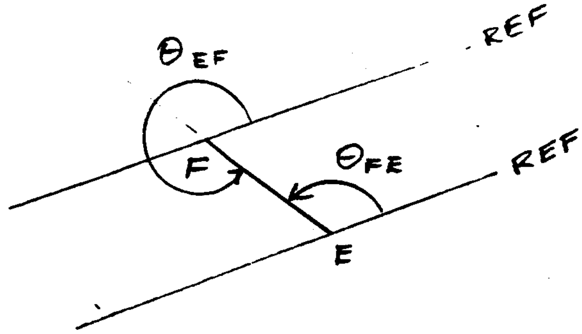
3. EFG Loop (Dipper Stick Loop)

$$R_{FE}\, e^{j\theta_{FE}} + R_{GF}\, e^{j\theta_{GF}} + R_{EG}\, e^{j\theta_{EG}}$$

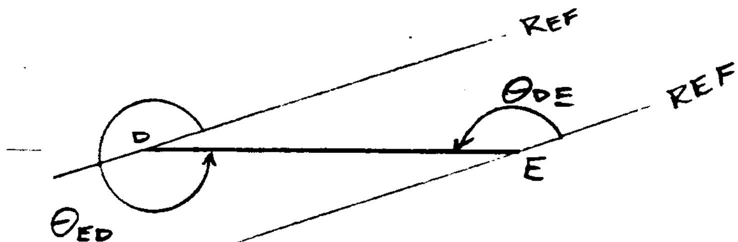
Terms:

R_{DA}	θ_{DA}
$R_{ED} = R_{DE}$	$\theta_{ED} = \theta_{DE} + 180°$ - see p. 13
R_{AE} - selected	$\theta_{AE} \equiv 180°$
R_{FD}	θ_{FD}
$R_{EF} = R_{FE}$	$\theta_{EF} = \theta_{FE} + 180°$ - see p. 13
R_{DE}	θ_{DE}
R_{FE}	θ_{FE}
R_{GF}	θ_{GF}
R_{EG} - selected	θ_{EG}

from p. 11 :

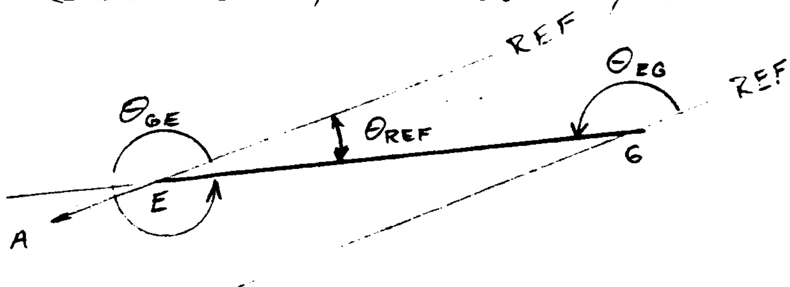


$$\theta_{EF} = \theta_{FE} + 180^\circ$$



$$\theta_{ED} = \theta_{DE} + 180^\circ$$

$\theta_{GE} = (360^\circ + \theta_{REF})$ ~ 360° required so that $\theta_{GE} > 0$



$$\theta_{GE} = \theta_{EG} + 180^\circ$$

$$(360^\circ + \theta_{REF}) = \theta_{EG} + 180^\circ$$

$$\theta_{EG} = (360^\circ + \theta_{REF}) - 180^\circ$$

$$= 180^\circ + \theta_{REF}$$

1. ADE Loop (Boom Link)

$$R_{DA} e^{j\theta_{DA}} + R_{ED} e^{j\theta_{ED}} + R_{AE} e^{j\theta_{AE}} = 0$$

$$R_{DA} \cos\theta_{DA} + R_{ED} \cos\theta_{ED} + R_{AE} \cos\theta_{AE} = 0$$

$$R_{DA} \sin\theta_{DA} + R_{ED} \sin\theta_{ED} + R_{AE} \sin\theta_{AE} = 0$$

$$\theta_{AE} \equiv 180^\circ \quad \therefore \quad \cos\theta_{AE} = -1$$
$$\sin\theta_{AE} = 0$$

$$R_{DA} \cos\theta_{DA} + R_{ED} \cos\theta_{ED} = R_{AE}$$

$$R_{DA} \sin\theta_{DA} + R_{ED} \sin\theta_{ED} = 0$$

$$\theta_{ED} = \theta_{DE} + 180^\circ \quad \therefore \quad \cos\theta_{ED} = \cos(\theta_{DE} + 180^\circ) = -\cos\theta_{DE}$$
$$\sin\theta_{ED} = \sin(\theta_{DE} + 180^\circ) = -\sin\theta_{DE}$$
and $R_{ED} = R_{DE}$

$$R_{DA} \cos\theta_{DA} - R_{DE} \cos\theta_{DE} = R_{AE} \checkmark$$
$$R_{DA} \sin\theta_{DA} - R_{DE} \sin\theta_{DE} = 0$$

2. DFE Loop

$$R_{FD} e^{j\theta_{FD}} + R_{EF} e^{j\theta_{EF}} + R_{DE} e^{j\theta_{DE}} = 0$$

$$R_{FD} \cos\theta_{FD} + R_{EF} \cos\theta_{EF} + R_{DE} \cos\theta_{DE} = 0$$

$$R_{FD} \sin\theta_{FD} + R_{EF} \sin\theta_{EF} + R_{DE} \sin\theta_{DE} = 0$$

$$\theta_{EF} = \theta_{FE} + 180^\circ \quad \therefore \quad \cos\theta_{EF} = -\cos\theta_{FE}$$
$$\sin\theta_{EF} = -\sin\theta_{FE}$$
and $R_{EF} = R_{FE}$

$$R_{FD}\cos\theta_{FD} - R_{FE}\cos\theta_{FE} + R_{DE}\cos\theta_{DE} = 0$$

$$R_{FD}\cos\theta_{FD} - R_{FE}\sin\theta_{FE} + R_{DE}\cos\theta_{DE} = 0$$

3. EFG Loop (Dipper Stick Link)

$$R_{FE}\,e^{j\theta_{FE}} + R_{GF}\,e^{j\theta_{GF}} + R_{EG}\,e^{j\theta_{EG}} = 0$$

$$R_{FE}\cos\theta_{FE} + R_{GF}\cos\theta_{GF} + R_{EG}\cos\theta_{EG} = 0$$

$$R_{FE}\sin\theta_{FE} + R_{GF}\sin\theta_{GF} + R_{EG}\cos\theta_{EG} = 0$$

Mid Stroke (MS)

Conditions:

$\theta_{FE_{ms}} = 90^\circ$

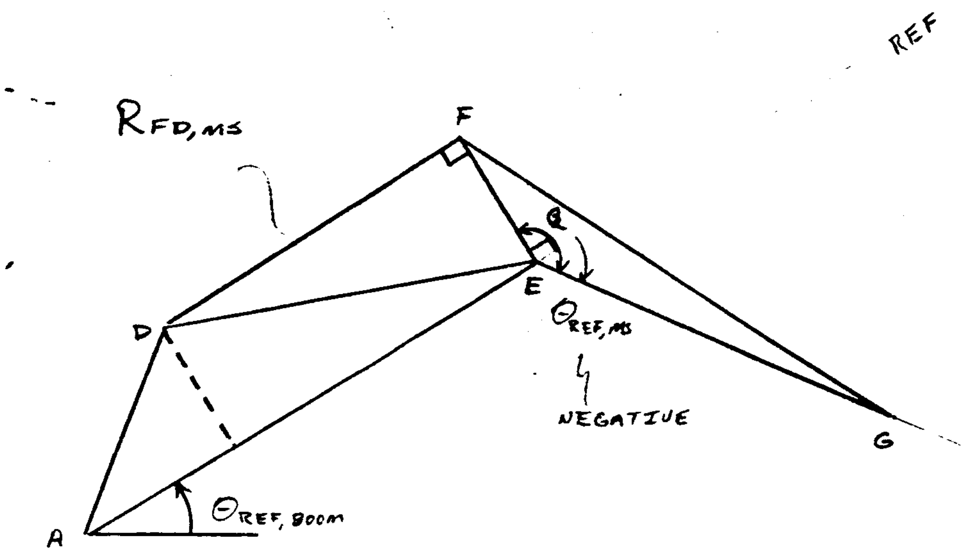
$\gamma_2 = 90^\circ$

Comments:

allows shortest cylinder

allows most advantageous transmission angle through the range of θ_{REF}

Mid-Stroke Position:



$$\theta_{REF,MS} = \frac{\theta_{REF,MAX} + \theta_{REF,MIN}}{2}$$

$$\beta = 90^\circ - \theta_{REF,MS}$$

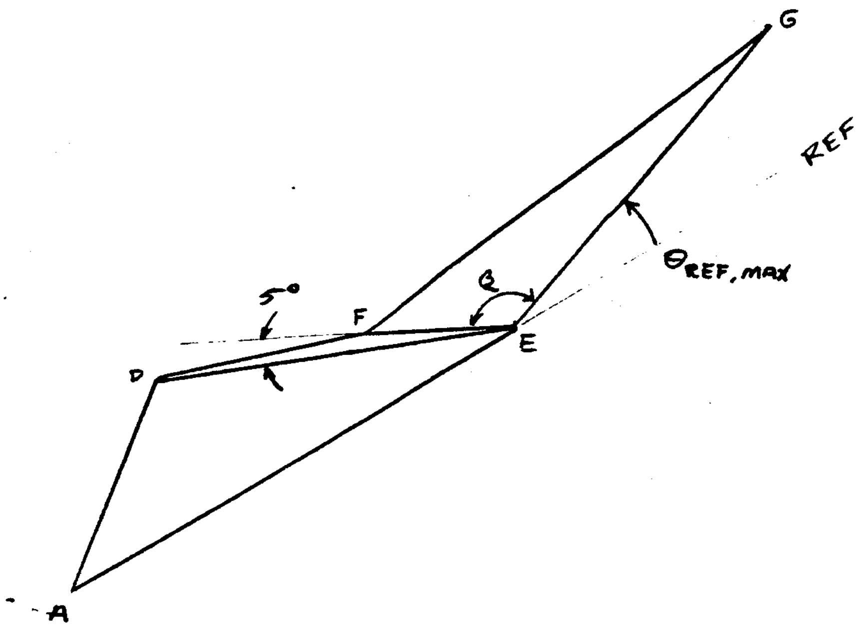
NEED BETTER ESTIMATE

Let $R_{FD,MAX} = 1.8\, R_{FD,MIN} \Rightarrow R_{FD,MS} = 1.4\, R_{FD,MIN}$

$$(1.4\, R_{FD,MIN})^2 = R_{DE}^2 - R_{FE}^2$$

$$R_{FE} = R_{DA} \sin\theta_{DA} = R_{DE} \sin\theta_{DE}$$ $\left(\begin{array}{l}\theta_{DA} < 25^\circ \\ R_{DA} > R_{DA}\end{array}\right)$

$\theta_{REF,\,MAX}$ Position:



$$(180° - \theta_{DE}) + 5° + (90° - \theta_{REF,\,MS}) + \theta_{REF,\,MAX} = 180°$$

$$180° - \theta_{DE} + 5° + 90° - \theta_{REF,\,MS} + \theta_{REF,\,MAX} = 180°$$

$$\theta_{DE} = \theta_{REF,\,MAX} - \theta_{REF,\,MS} + 95°$$

$$R_{FD,\,MIN}^2 = R_{DE}^2 + R_{FE}^2 - 2 R_{DE} R_{FE} \cos 5°$$

$$= R_{DE}^2 + R_{FE}^2 - \underbrace{(2 \cos 5°)}_{\approx\, 1.9924} R_{DE} R_{FE}$$

$$R_{DA}\cos\theta_{DA} - R_{DE}\cos\theta_{DE} = R_{AE}$$

$$R_{DA}\sin\theta_{DA} - R_{DE}\sin\theta_{DE} = 0$$

Terms:

R_{DA}	θ_{DA}
R_{DE}	θ_{DE} - known
R_{AE} - known	

Constrants: $R_{DA} > R_{AB}$

$\theta_{DA} \leq 25°$

Iterative Solution:

- Set $\theta_{DA} = 25°$
- Solve Equations Simultaneously
- Check $R_{DA} \geq 1.2\, R_{BA}$

  If no, let $\theta_{DA} = \theta_{DA} - 1°$

  If yes:

R_{DA}, R_{DE}, $\theta_{DA} \Rightarrow$ known

Solve for R_{DA} & R_{DE}

$$R_{DA} \cos \theta_{DA} - R_{DE} \cos \theta_{DE} = R_{AE}$$
$$R_{DA} \sin \theta_{DA} - R_{DE} \sin \theta_{DE} = 0$$

$$R_{DA} \sin \theta_{DA} = R_{DE} \sin \theta_{DE}$$

$$R_{DA} = \frac{R_{DE} \sin \theta_{DE}}{\sin \theta_{DA}}$$

$$\left(\frac{R_{DE} \sin \theta_{DE}}{\sin \theta_{DA}} \right) \cos \theta_{DA} - R_{DE} \cos \theta_{DE} = R_{AE}$$

$$R_{DE} \left(\frac{\sin \theta_{DE} \cos \theta_{DA}}{\sin \theta_{DA}} - \cos \theta_{DE} \right) = R_{AE}$$

$$R_{DE} \left(\frac{\sin \theta_{DE} \cos \theta_{DA} - \cos \theta_{DE} \sin \theta_{DA}}{\sin \theta_{DA}} \right) = R_{AE}$$

$$\sin(\alpha - \beta) = \sin \alpha \cos \beta - \cos \alpha \sin \beta$$

$$R_{DE} \left[\frac{\sin(\theta_{DE} - \theta_{DA})}{\sin \theta_{DA}} \right] = R_{AE}$$

$$R_{DE} = R_{AE} \left[\frac{\sin \theta_{DA}}{\sin(\theta_{DE} - \theta_{DA})} \right]$$

$$R_{DA} = \frac{R_{DE} \sin \theta_{DE}}{\sin \theta_{DA}} = R_{AE} \left[\frac{\sin \theta_{DA}}{\sin(\theta_{DE} - \theta_{DA})} \right] \frac{\sin \theta_{DE}}{\sin \theta_{DA}}$$

$$R = R_{AE} \left[\frac{\sin \theta_{DE}}{(\theta_{DE} - \theta_{DA})} \right]$$

$$(1.4)^2 R_{FD,MIN}^2 = R_{DE}^2 - R_{FE}^2$$ -p.16

$$R_{FD,MIN}^2 = R_{DE}^2 + R_{EE}^2 - (2\cos 5^\circ) R_{DE} R_{FE}$$ -p.17

$$2.96\, R_{FD,MIN}^2 = 2R_{DE}^2 - (2\cos 5^\circ) R_{DE} R_{FE}$$

$$R_{FE} = R_{DE} \sin \theta_{DE}$$ -p.16

$$2.96\, R_{FD,MIN}^2 = 2R_{DE}^2 - (2\cos 5^\circ) R_{DE}^2 \sin \theta_{DE}$$
$$= 2R_{DE}^2 (1 - (\cos 5^\circ) \sin \theta_{DE})$$

$$R_{FD,MIN}^2 = \frac{R_{DE}^2 [1 - (\cos 5^\circ) \sin \theta_{DE}]}{1.48}$$

$$R_{FD,MIN} = \left(\frac{1 - (\cos 5^\circ) \sin \theta_{DE}}{1.48} \right)^{1/2} R_{DE}$$

$$R_{FE} = R_{DE} \sin \theta_{DE}$$

$$R_{FD} \cos \theta_{FD} - R_{FE} \cos \theta_{FE} + R_{DE} \cos \theta_{DE} = 0$$

$$R_{FD} \sin \theta_{FD} - R_{FE} \sin \theta_{FE} + R_{DE} \sin \theta_{DE} = 0$$

Terms:

R_{FD} - variable, given θ_{FD}

R_{FE} - known, see above θ_{FE}

R_{DE} - known, see p. 19 θ_{DE} - known, see p.17

Solve the above equations simultaneously for θ_{FD} & θ_{FE}.

Isolate θ_{FD} terms:

$$-R_{FD}\cos\theta_{FD} = -R_{FE}\cos\theta_{FE} + R_{DE}\cos\theta_{DE}$$
$$-R_{FD}\sin\theta_{FD} = -R_{FE}\sin\theta_{FE} + R_{DE}\sin\theta_{DE}$$

Square both sides of these equations:

$$R_{FD}^2\cos^2\theta_{FD} = R_{FE}^2\cos^2\theta_{FE} + R_{DE}^2\cos^2\theta_{DE} - 2R_{FE}\cos\theta_{FE}R_{DE}\cos\theta$$
$$R_{FD}^2\sin^2\theta_{FD} = R_{FE}^2\sin^2\theta_{FE} + R_{DE}\sin^2\theta_{DE} - 2R_{FE}\sin\theta_{FE}R_{DE}\sin\theta$$

Add the two equations together:

$$R_{FD}^2 = R_{FE}^2 + R_{DE}^2 - 2R_{FE}R_{DE}(\cos\theta_{FE}\cos\theta_{DE} + \sin\theta_{FE}\sin\theta_{DE})$$

$$\cos(\alpha-\beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta$$

$$R_{FD}^2 = R_{FE}^2 + R_{DE}^2 - 2R_{FE}R_{DE}\cos(\theta_{FE} - \theta_{DE})$$

$$\cos(\theta_{FE} - \theta_{DE}) = \frac{R_{FD}^2 - R_{FE}^2 - R_{DE}^2}{-2R_{FE}R_{DE}}$$

$$\theta_{FE} - \theta_{DE} = \cos^{-1}\left(\frac{R_{FD}^2 - R_{FE}^2 - R_{DE}^2}{-2R_{FE}R_{DE}}\right)$$

$$\theta_{FE} = \theta_{DE} + \cos^{-1}\left(\frac{R_{FD}^2 - R_{FE}^2 - R_{DE}^2}{-2R_{FE}R_{DE}}\right)$$

Isolate θ_{FE} terms:

$$R_{FE}\cos\theta_{FE} = R_{FD}\cos\theta_{FD} + R_{DE}\cos\theta_{DE}$$
$$R_{FE}\sin\theta_{FE} = R_{FD}\sin\theta_{FD} + R_{DE}\sin\theta_{DE}$$

Square both sides of these equations:

$$R_{FE}^2\cos^2\theta_{FE} = R_{FD}^2\cos^2\theta_{FD} + R_{DE}^2\cos^2\theta_{DE} + 2R_{FD}\cos\theta_{FD}\,R_{DE}\cos\theta_{DE}$$
$$R_{FE}^2\sin^2\theta_{FE} = R_{FD}^2\sin^2\theta_{FD} + R_{DE}^2\sin^2\theta_{DE} + 2R_{FD}\sin\theta_{FD}\,R_{DE}\sin\theta_{DE}$$

Add the two equations together:

$$R_{FE}^2 = R_{FD}^2 + R_{DE}^2 + 2R_{FD}R_{DE}(\cos\theta_{FD}\cos\theta_{DE} + \sin\theta_{FD}\sin\theta_{DE}$$

$$R_{FE}^2 = R_{FD}^2 + R_{DE}^2 + 2R_{FD}R_{DE}\cos(\theta_{FD} - \theta_{DE})$$

$$\cos(\theta_{FD} - \theta_{DE}) = \frac{R_{FE}^2 - R_{FD}^2 - R_{DE}^2}{2R_{FD}R_{DE}}$$

$$\theta_{FD} - \theta_{DE} = \cos^{-1}\left(\frac{R_{FE}^2 - R_{FD}^2 - R_{DE}^2}{2R_{FD}R_{DE}}\right)$$

$$\theta_{FD} = \theta_{DE} + \cos^{-1}\left(\frac{R_{FE}^2 - R_{FD}^2 - R_{DE}^2}{2R_{FD}R_{DE}}\right)$$

$$R_{FE}\cos\theta_{FE} + R_{GF}\cos\theta_{GF} + R_{EG}\cos\theta_{EG} = 0$$

$$R_{FE}\sin\theta_{FE} + R_{GF}\sin\theta_{GF} + R_{EG}\sin\theta_{EG} = 0$$

Terms

R_{FE} - known, see p20

R_{GF} - known, see below

R_{EG} - known, selected

θ_{FE} - known, see p.21

θ_{GF}

θ_{EG}

$$R_{GF} = (R_{FE}^2 + R_{EG}^2 - 2R_{FE}R_{EG}\cos\beta)^{1/2}$$

Solve the above equations simultaneously for θ_{GF} & θ_{EG}

Isolate θ_{GF} terms:

$$-R_{GF}\cos\theta_{GF} = R_{FE}\cos\theta_{FE} + R_{EG}\cos\theta_{EG}$$
$$-R_{GF}\sin\theta_{GF} = R_{FE}\sin\theta_{FE} + R_{EG}\sin\theta_{EG}$$

Square both sides and add:

$$R_{GF}^2 = R_{FE}^2 + R_{EG}^2 + 2R_{FE}R_{EG}\cos(\theta_{FE} - \theta_{EG})$$

$$\cos(\theta_{FE} - \theta_{EG}) = \frac{R_{GF}^2 - R_{FE}^2 - R_{EG}^2}{2R_{FE}R_{EG}}$$

$$\theta_{FE} - \theta_{EG} = \cos^{-1}\left(\frac{R_{GF}^2 - R_{FE}^2 - R_{EG}^2}{2R_{FE}R_{EG}}\right)$$

$$\theta_{EG} = \theta_{FE} - \cos^{-1}\left(\frac{R_{GF}^2 - R_{FE}^2 - R_{EG}^2}{2R_{FE}R_{EG}}\right)$$

similarly:

$$R_{EG}^2 = R_{FE}^2 + R_{GF}^2 + 2R_{FE}R_{GF}\cos(\theta_{FE} - \theta_{GF})$$

$$\theta_{GF} = \theta_{FE} - \cos^{-1}\left(\frac{R_{EG}^2 - R_{FE}^2 - R_{GF}^2}{2R_{FE}R_{GF}}\right)$$

$$\theta_{REF,DIPPER} = \theta_{EG} - 180^\circ$$